

MILITARY ACADEMY
MILITARY ENGINEERING COLLEGE
RASHEED CAMP- BAGHDAD – IRAQ

MONOGRAPH ON DIRECT CURRENT
ELECTRICAL MACHINES

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CHAPTER 1 : PRINCIPLE OF OPERATION1.1 Some basic rules

Right-hand screw rule $\equiv$ cross product operation in vector algebra :

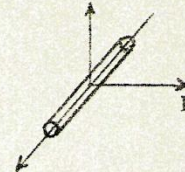
$$\mathbf{A}_1 \times \mathbf{A}_2 = \mathbf{A}_3$$

$\mathbf{A}_1$, $\mathbf{A}_2$, and $\mathbf{A}_3$ are vectors. Rotate RH fingers from the direction of the first vector, $\mathbf{A}_1$, to the direction of the second vector, $\mathbf{A}_2$, through the small angle ($< 180^\circ$) between them; the direction of $\mathbf{A}_3$ is then given by the extended RH thumb. In our applications, the magnetic field $\mathbf{B}$ is always the second vector.

Given a straight conductor moving in a magnetic field, and oriented perpendicular to the direction of the field. Let

B = magnetic flux density (also called magnetic induction), [T = tesla = weber/m²];

l = active length of conductor, [m].



Induced voltage (emf) : $\mathcal{E} = B l u \sin \alpha$ volts

u = speed of conductor perpendicular to its length [m/s];

α = small angle from u to B .

Direction of $\mathcal{E}$: RH screw rule from u to B .

Developed force : $F_d = B i l$ newtons [N]

i = current through conductor, [A].

Direction of F_d : RH screw rule from i to B .

1.2 Single conductor

Consider a straight conductor moving at a uniform speed u in a uniform magnetic field B , and carrying a current I . Let

l = active length (i.e. length of conductor segment immersed in the field);

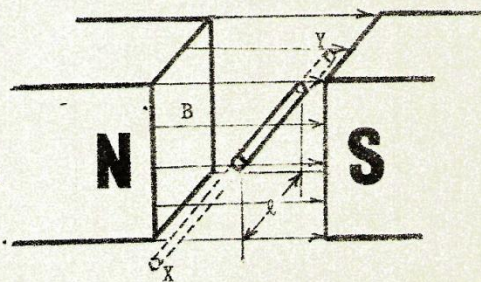
F_m = applied mechanical force, [N].

$$\left. \begin{matrix} u \\ B \end{matrix} \right\} \Rightarrow \mathcal{E} = B l u \quad \text{and} \quad \left. \begin{matrix} i \\ B \end{matrix} \right\} \Rightarrow F_d = B I l$$

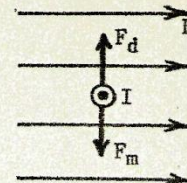
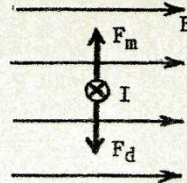
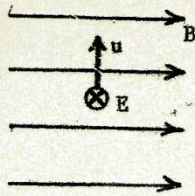
$$EI = (B l u) I = (B I l) u = F_d u \quad \Rightarrow \quad EI = F_d u = P_c = \text{conversion power}$$

NB Because the speed u is constant, F_d and F_m must be equal and opposite (otherwise there would be acceleration or deceleration).

EI is electrical power, and $F_d u$ ($= F_m u$) is mechanical power.



1.2

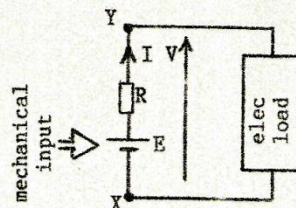
Directions

I in direction of E;
 F_d opposite to u.
 $\Rightarrow$ generator action.

I opposite to E;
 F_d in direction of u.
 $\Rightarrow$ motor action.

$$(R = \frac{\rho l_T}{A})$$

= total resistance of conductor)



$$V = E - IR$$

$$P_{in} = \frac{\Delta W_m}{\Delta t} = \frac{F_m \Delta S}{\Delta t}$$

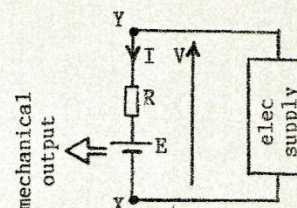
$$= F_d u = P_c$$

$$P_{out} = VI = (E - IR)I$$

$$= EI - I^2 R = P_c - P_{Cu}$$

$$\Rightarrow P_{out} = P_{in} - P_{Cu}$$

$$P_{in} - P_{out} = P_{Cu}$$



$$V = E + IR$$

$$P_{in} = VI = (E + IR)I$$

$$= EI + I^2 R = P_c + P_{Cu}$$

$$P_{out} = \frac{\Delta W_m}{\Delta t} = \frac{F_m \Delta S}{\Delta t}$$

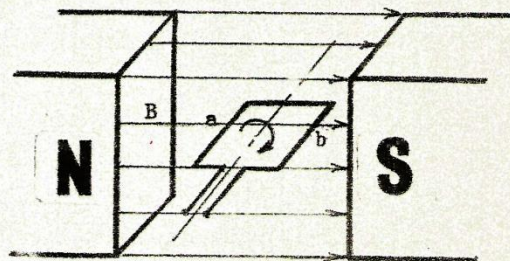
$$= F_d u = P_c$$

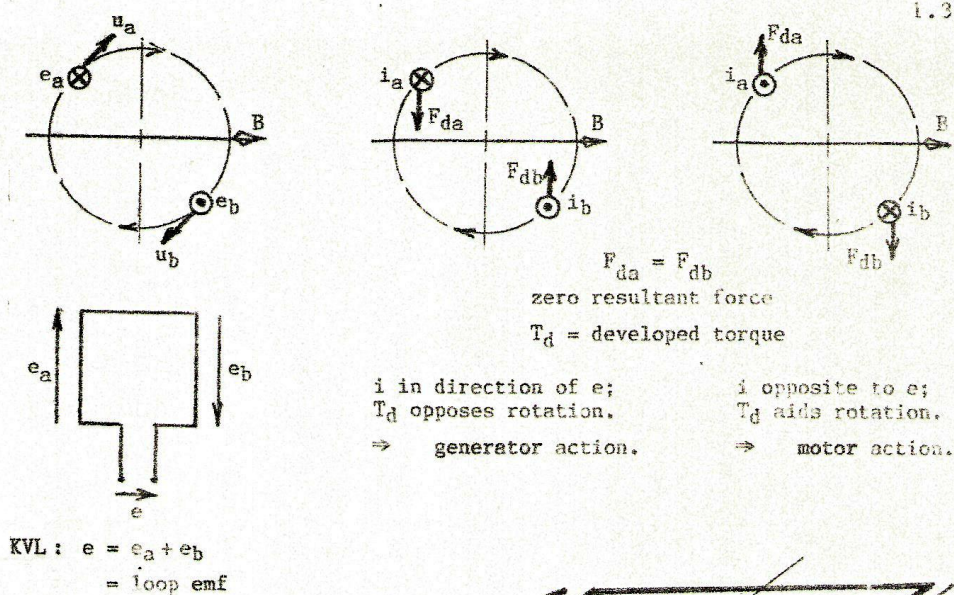
$$\Rightarrow P_{in} = P_{out} + P_{Cu}$$

$$P_{in} - P_{out} = P_{Cu}$$

1.3 Wire loop

Consider now a wire loop rotating at a uniform speed in a magnetic field B. Conductors a and b are the active parts of the loop; the remaining parts are 'end-connections' and 'leads'.





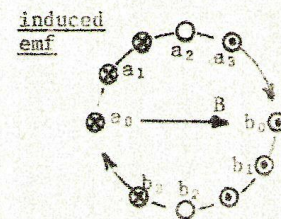
1.4 Slip rings

Slip rings and brushes may be used to make electrical contact with a rotating loop. Slip rings rotate with loop, while brushes are stationary to give sliding contact.

A slip ring and a brush for each terminal.

position	induced emf	developed torque
0, 1	+ve	CW
2	zero	zero
3	-ve	CCW

The induced emf is alternating, and the developed torque oscillates (about the vertical position). Clearly, slip rings are not suitable for dc machines (they are used in ac machines).



1.5 Commutator

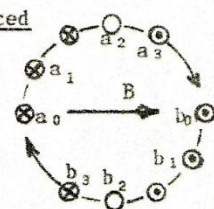
A commutator is a conducting ring split into segments; each segment is electrically connected to one terminal of the loop. It is mounted on the shaft, but is electrically insulated from it. The brushes are stationary and make sliding contact with the segments.

A_2 is always positive;
 A_1 is always negative :-

$\Rightarrow e_t$ always positive, &
 T_d always CW.

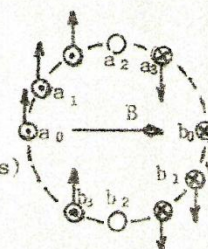
(but emf & current within loop oscillate.)

induced emf



developed torque

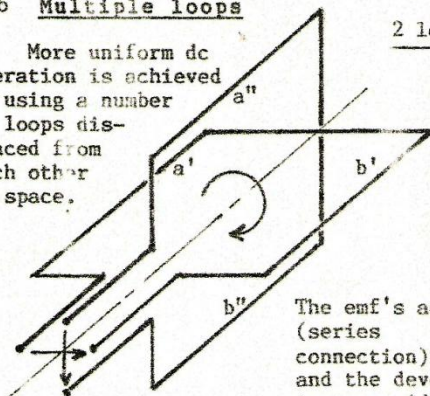
(direct current supplied to brushes)



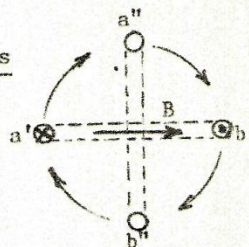
Although e_t and T_d are now unidirectional (i.e. remain in the same direction or sense), they do not represent steady dc operation because they fluctuate: each is maximum when the loop is in position 0, and zero when it is in position 2.

1.6 Multiple loops

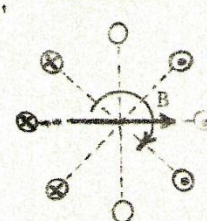
More uniform dc operation is achieved by using a number of loops displaced from each other in space.



2 loops



4 loops

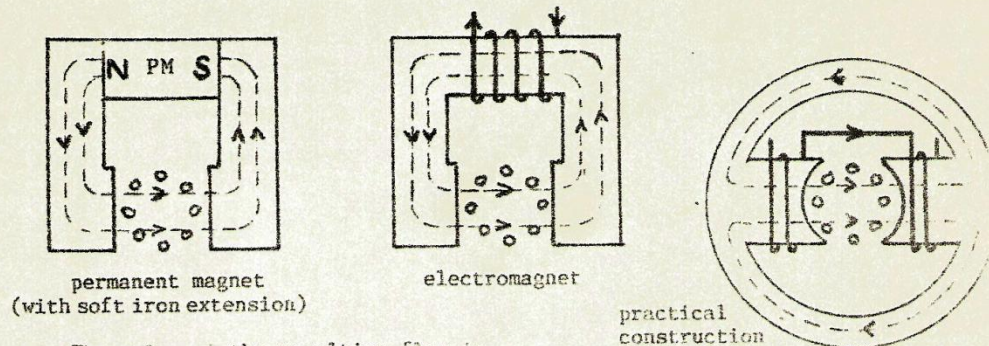


The emf's add (series connection), and the developed torques aid each other. As the number of loops is increased, ideal dc operation is approached.

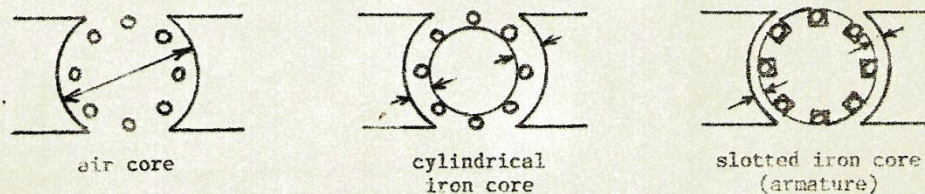
1.5

1.7 Magnetic circuit

The magnetic field may be obtained by means of permanent magnets (PM), or, more commonly, by means of electromagnets (field coils with iron cores).



The value of the resulting flux is determined by the mmf (of the PM or electromagnet) and the magnetic reluctance in the path of the flux. Iron has very high magnetic permeability, so that it is the air gap in the path of the flux that limits its value. The air gap must therefore be made short.



The air gap cannot be avoided completely (why ?)

1.8 Multiple poles

A dc machine can have 2, 4, 6, 8, ... poles (an even number - why ?) Let

$2p$ = number of poles;

i.e. p = number of pole pairs.

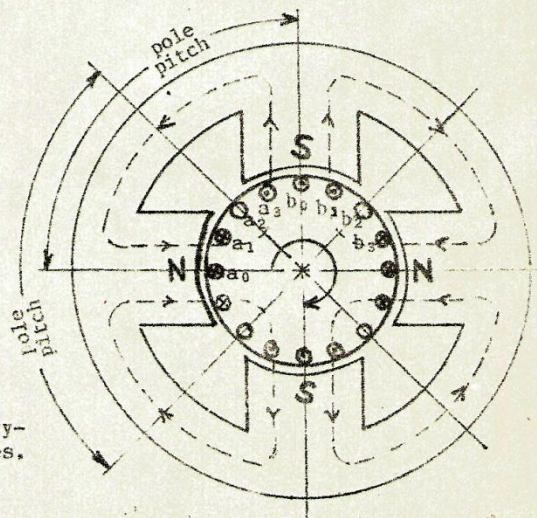
one revolution $\equiv 360$ mech degrees

one pole pair $\equiv 360$ elec degrees

$\Rightarrow$ elec angle = $p \times$ mech angle

pole pitch $\equiv 180^\circ \text{ elec} \equiv \frac{360^\circ \text{ mech}}{2p}$

Each armature loop is placed over one pole pitch. Electrically, everything repeats after two pole pitches.



1.9 Loop emf

D = diameter of the armature [m];

ℓ = active length [m].

n = rotational speed [rps = revolutions per second];

u = speed = $\pi D n$ [m/s];

ω_r = angular speed = $2\pi n$ [rad/s].

$2p$ = number of poles,

p = number of pole pairs.

A_p = armature surface area
corresponding to one pole pitch

$$= \frac{\pi D \ell}{2p} \text{ [m}^2\text{]}.$$

ϕ = flux per pole [Wb = weber]; total
magnetic flux through pole face;
same for all poles;

B = air gap flux density [T = tesla = Wb/m²]; normal field at armature surface;

B_{av} = average air gap flux density [T].

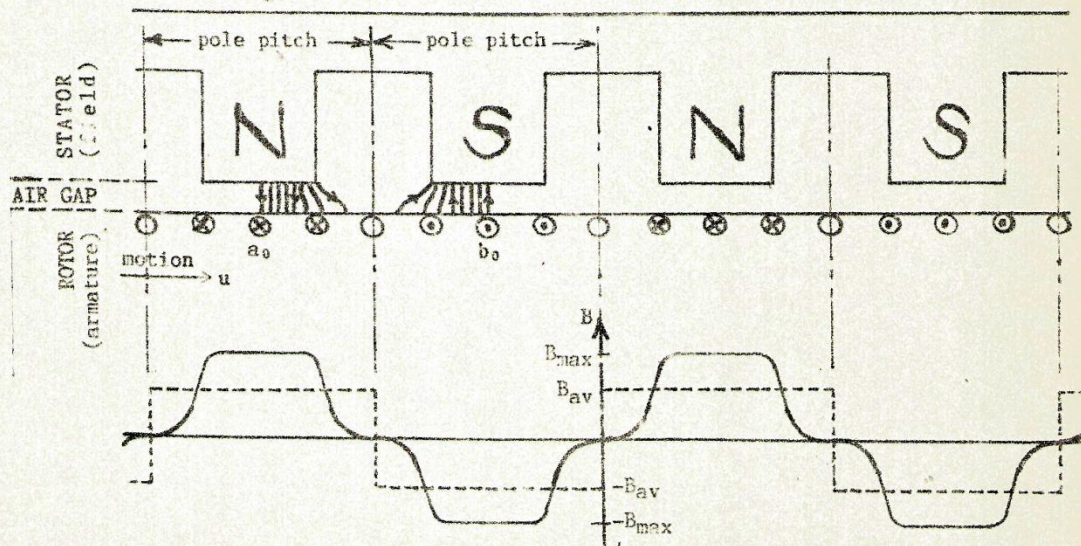
$$\phi = \int_{A_p} B \, dA; \quad B_{av} = \frac{\phi}{A_p}.$$

The actual air gap flux density B is distributed around the periphery of the armature as shown below. The average gap flux density B_{av} is constant over a pole pitch. Consider side "a" of the wire loop; the instantaneous emf is

$$e_a = B \ell u \quad (e_a(t) \text{ has the same waveshape as } B)$$

The average emf induced in side "a" is

$$E_a = B_{av} \ell u \quad (\text{constant over alternate pole pitches})$$



1.7

Average commutated emf

wire loop : $E_{loop} = E_a + E_b = 2 B_{av} l u = 2 \pi D l n B_{av}$
 $= (2 \pi D l n) (\phi / \lambda_p) = 4 p n \phi = \frac{2p}{\pi} \omega_r \phi$ $(= \frac{\Delta \phi}{\Delta t} = \frac{2 \phi}{\frac{1}{2pn}})$

conductor (one side of loop) :

$$E_{con} = \frac{1}{2} E_{loop} = B_{av} l u = \pi D l n B_{av} = 2 p n \phi = \frac{p}{\pi} \omega_r \phi$$

coil (N = number of turns = number of loops in series) :

$$E_{coil} = N \times E_{loop} = 2 N B_{av} l u = 2 \pi D l N n B_{av} = 4 p N n \phi = \frac{2p}{\pi} N \omega_r \phi \quad (= N \frac{\Delta \phi}{\Delta t})$$

$$= 2 N B_{av} l u = 2 \pi D l N n B_{av} = 4 p N n \phi = \frac{2p}{\pi} N \omega_r \phi$$

1.10 Loop torque

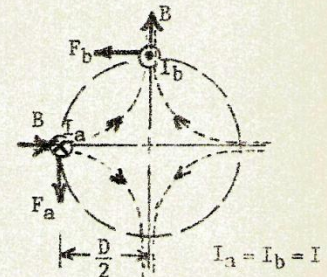
The instantaneous force on side "a" is

$$f_a = B I_a l$$

The normal field B varies over a pole pitch, and hence f_a also varies. The average force on side "a" is

$$F_a = B_{av} I_a l$$

B_{av} , and hence F_a , are constant over a pole pitch corresponding to a given pole. Moreover, because of commutation, I_a reverses over the next pole pitch so that F_a remains in the same sense around the axis of the armature. The resultant force due to all armature conductors is zero, but there is developed torque because all forces act in the same sense around the axis.

Average developed torque

wire loop : $T_{loop} = F_a \frac{D}{2} + F_b \frac{D}{2} = \frac{D}{2} (B_{av} I_a l + B_{av} I_b l) = D l I B_{av} \quad [\text{Nm}]$
 $= D l I (\phi / \lambda_p) = \frac{2p}{\pi} I \phi$

coil (N turns) : $T_{coil} = N \times T_{loop} = D l N I B_{av} = \frac{2p}{\pi} N I \phi$

For constant rotational speed n , and assuming no friction, the developed torque is equal to the applied mechanical torque.

1.8

1.11 Conversion power

A dc machine may run as a generator or as a motor. In each of the two modes of operation, there is induced emf and developed torque (given by the equations of sections 1.9 and 1.10). What determines the mode (generator or motor) is the directional relationship between E and I , and between T_d and n :

generator mode: I with E , T_d opposite n ;

motor mode: I opposite E , T_d with n .

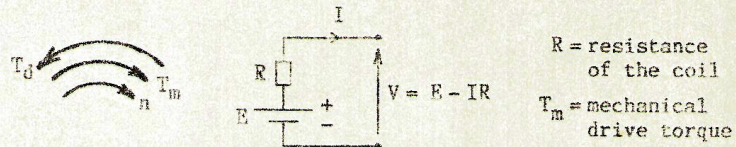
Recall the coil equations of sections 1.9 and 1.10; with $E = E_{\text{coil}}$ and $T_d = T_{\text{coil}}$, we can write

$$EI = (4pN\Phi)\dot{\theta} = 4pN\frac{\omega_r}{2\pi}\Phi I = \left(\frac{2p}{\pi}NI\Phi\right)\omega_r = T_d\omega_r$$

This represents electromechanical energy conversion. The conversion power is defined as

$$P_c = EI = T_d\omega_r \quad \begin{cases} EI \text{ on the electrical side} \\ T_d\omega_r \text{ on the mechanical side} \end{cases}$$

Generator action:

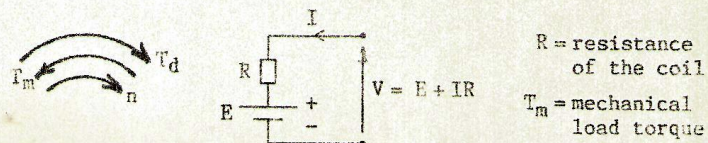


$$\text{mech i/p: } P_{\text{in}} = \omega_r T_d = P_c$$

$$\text{elec o/p: } P_{\text{out}} = VI = (E - IR)I = EI - I^2R = P_c - P_{\text{Cu}}$$

$$\Rightarrow P_{\text{out}} = P_{\text{in}} - P_{\text{Cu}}$$

Motor action:



$$\text{elec i/p: } P_{\text{in}} = VI = (E + IR)I = EI + I^2R = P_c + P_{\text{Cu}}$$

$$\text{mech o/p: } P_{\text{out}} = \omega_r T_d = P_c$$

$$\Rightarrow P_{\text{out}} = P_{\text{in}} - P_{\text{Cu}}$$

More generally,

$$P_{\text{out}} = P_{\text{in}} - \text{losses}$$

where the losses include (in addition to copper losses) mechanical losses (friction and windage), and iron losses (hysteresis and eddy current).

CHAPTER 2 : CONSTRUCTION

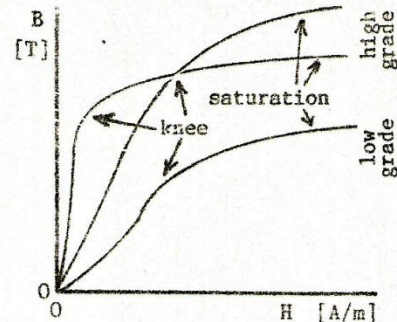
2.1

Electrical machines are essentially electrical and magnetic circuits coupled to each other to develop emf's and torques. The figure on page 2.2 shows some general constructional features of dc machines. Actual machines can vary greatly in details.

2.1 Materials

- a. Iron: high magnetic permeability
 ⇒ minimise reluctance of magnetic circuit
 ⇒ high working fields

High grade steel (eg silicon steels) for magnetic cores. Lower grade steels (eg cast iron, cast steel, mild steel) for constructional parts. Relative permeability of the linear part of the magnetisation (BH-) curve is of the order of 1000, and is higher for higher grade steels. Saturation limits maximum flux density in iron to 2 T or less; the resulting average gap flux density is then around 0.8 T for practical industrial machines.



- b. Copper: high electric conductivity
 ⇒ minimise resistance of electric circuits
 ⇒ high working currents

Aluminum is seldom used because of space limitations; (why is silver not used either ?)

- c. Air: air gap in path of flux necessary to allow motion.

- d. Insulating materials: necessary to insulate conductors from each other and from adjacent iron parts (which are also conducting).

The economic factor: machines are generally designed to yield the required performance at minimum cost.

Cost: cost of materials + cost of manufacture.

Required performance: described in terms of operating voltage, current, power, torque, speed, efficiency, weight, volume, reliability, temperature rise, function, noise, etc.

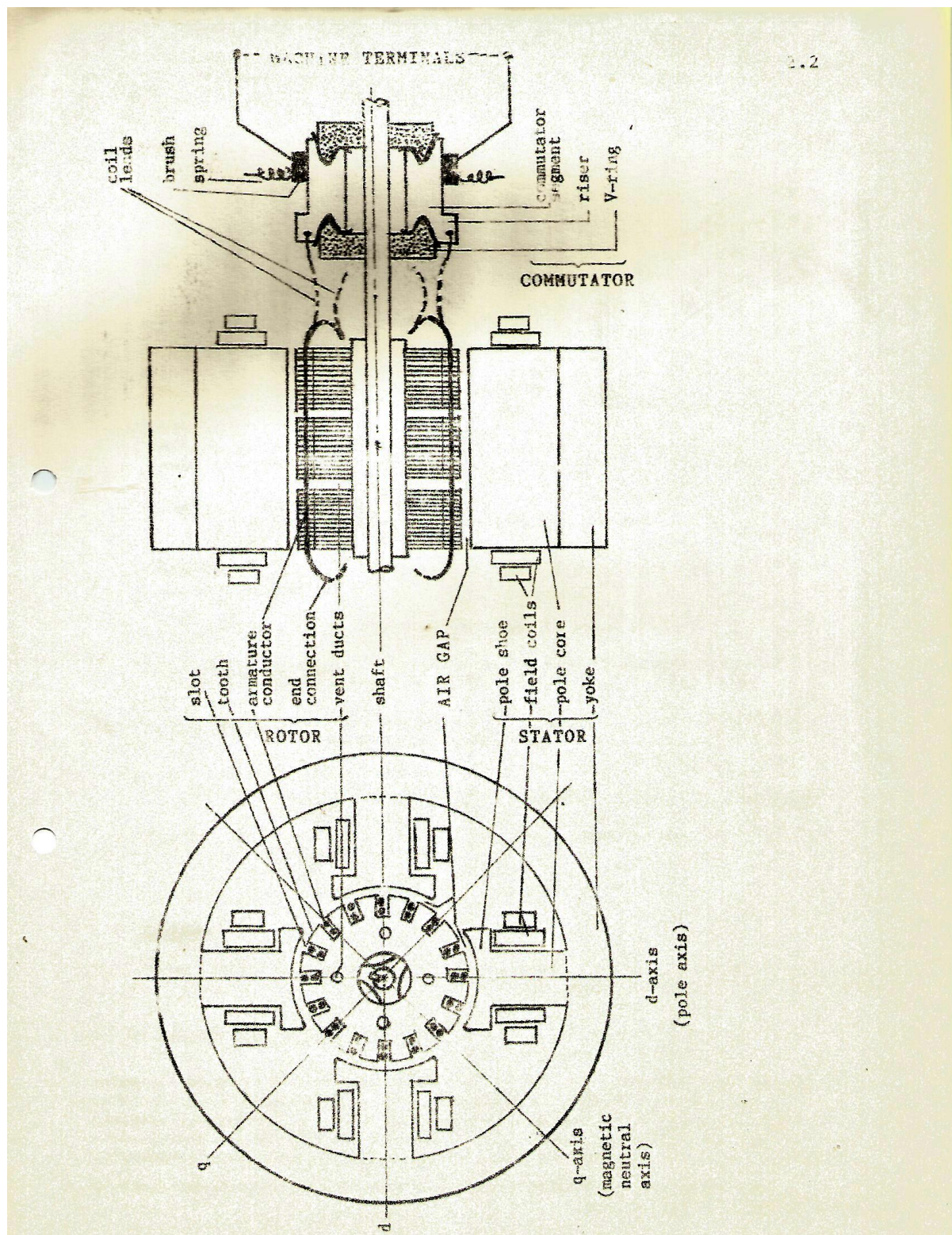
2.2 Losses

Power losses in dc machines include: copper losses (I^2R losses in conductors); iron losses (hysteresis & eddy currents); friction and windage.

All losses are undesirable because: they represent wasted power, and cause the temperature to rise.

Materials retain their desired properties (electrical, magnetic, and mechanical) within specific temperature limits. Temperature rise is most critical to insulating materials: their insulation deteriorates at sufficiently high temperatures (around 100 °C, depending on the particular insulator), and ultimately breaks down causing short circuits and possibly total machine failure.

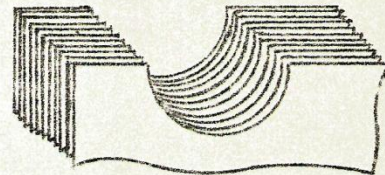
To limit temperature rise, the machine design must minimise losses, and provide for efficient ventilation.



In general, heat is generated throughout the volume of the conductor or iron core, but can be dissipated only through its surface. To improve cooling of such parts, their surfaces must be made larger, which means that machines become bigger.

Changing magnetic fields induce emf's not only in copper conductors (which is desirable), but also in iron parts. As iron has a relatively small resistivity, currents will circulate in it. These 'eddy currents' distort the field distribution and, more important, yield I^2R losses in the iron. To limit these losses, and the resulting temperature rise, some cores are made of steel laminations (instead of solid steel); these are punched sheets (or stampings) around 0.5-1.0 mm thick with insulated facets (paper or suitable coating) stacked and bolted together. The laminations are stacked in the direction of the induced emf so that the insulated surfaces will be in the way of circulating currents.

$$\text{stacking factor} = \frac{\text{useful length}}{\text{total length}} \approx 0.90-0.97$$



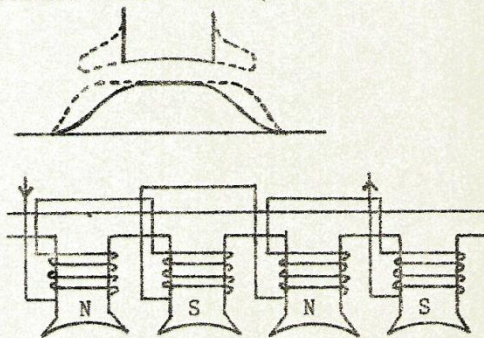
MAIN PARTS OF A DC MACHINE (see figure on page 2.2)

2.3 Stator (field)

Yoke: lower grade steel; supports poles; return path for flux; encloses machine.

Poles: core and shoes; high grade steel. Pole core may or may not be laminated. Pole shoes are usually laminated (flux fluctuation due to rotating armature slots). Pole shoes (i) reduce reluctance of the air gap (by increasing its area); (ii) improve flux density distribution in the air gap; and (iii) provide mechanical support for the field coils.

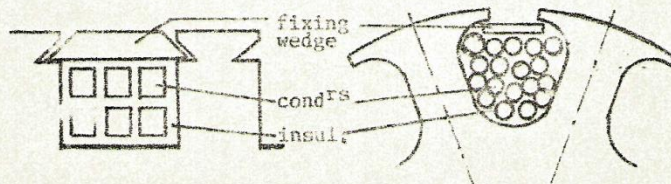
Field coils: provide the mmf for the main working flux. There may be more than one set of coils, i.e. 2 or more coils on each pole. The coils of one set are identical to each other, and are connected together electrically.



2.4 Rotor (armature)

The armature is made of high-grade steel laminations punched and stacked together to form a cylinder or drum. It is mounted on the shaft (directly for small machines, and by means of a 'spider' for larger machines). It may have radial and axial ventilation ducts for cooling.

The armature windings are placed in slots around the armature periphery. The conductors are held in place by wedges, or by bands wrapped around the armature. The slots are sometimes skewed to reduce noise.



2.4

2.5 Air gap

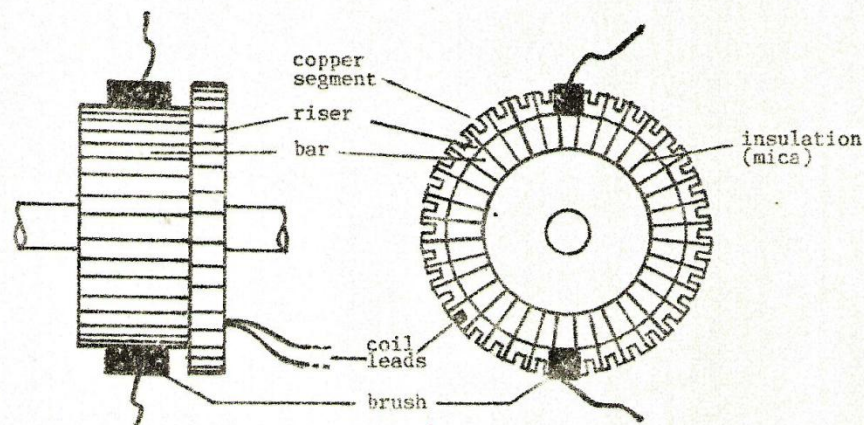
The air gap is the space between stator and rotor needed to allow relative motion between them (i.e. it is mechanically necessary). Magnetically, it introduces a high reluctance in the path of the working flux (most of the field mmf is consumed in the air gap); it is therefore made as short as possible, typically 0.5-5.0 mm. The armature surface and the pole shoes facing it require precise machining to avoid asymmetry and vibration.

2.6 Commutator

The function of the commutator is to interface between the alternating currents and emf's in the rotating armature coils on the one side, and the direct current and voltage at the machine terminals. It is made up of copper segments insulated from each other and mounted on the shaft (i.e. it rotates with the rotor) in a cylindrical form. V-rings hold the bars in place. The leads of each armature coil are connected to risers (each of the two leads of a coil goes to a different commutator segment).

Brushes are carbon or graphite blocks mounted in stationary holders with spring pressure to maintain good electrical contact with the rotating commutator segments. The brushes wear out with time and must be replaced regularly.

The commutator is a critical part of the machine: brushes wear out and must be replaced, and carbon filings and dirt accumulate causing current leakage between segments. Intermittent contact between brushes and segments often leads to sparking, which may become quite serious.



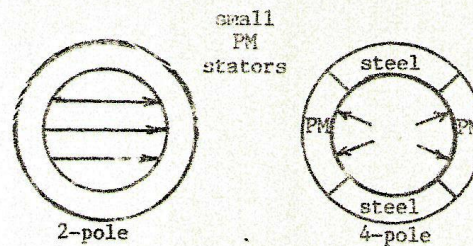
2.7 Mechanical items

Shaft; spider; bearings (with grease pack or lubrication system).
 Bolts; clamps; spacers; brackets.
 Enclosure (frame); ventilation windows. Lifting eye; base.
 Terminal box. Shaft mounted fan. Brush gear.
 Etc.

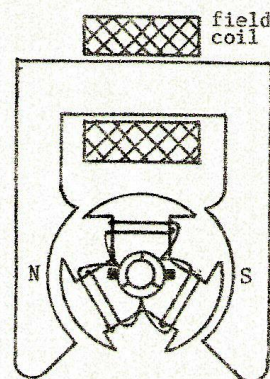
2.5

2.3 Small (miniature) machines

Very small dc motors are often made with PM fields. The 2-pole machine shown has an 'annular' magnet that may be cross-magnetised as shown, or it may be radially magnetised. The magnet fits within a steel housing which provides the yoke. The steel blocks in the 4-pole machine shown may be replaced by PM's (at extra cost).



For such miniature machines, the armature may have three slots (and three teeth) as shown, or it may have five slots and teeth. The current-excited field shown may be replaced by a PM. Note carefully the connection of the three armature coils to the three-segment commutator; also note the location of the brushes.



2.9 Machine ratings

The 'nameplate' of a machine serves to identify the machine. It gives rated voltage, current, power, speed, and possibly other data useful to the user. The machine ratings are the values of the various parameters for which the machine will run continuously without overheating or other damage. In practice, the ratings can be exceeded for short periods. If, however, the ratings are exceeded for considerable periods of time, there may be permanent damage, particularly to insulation.

Machines are usually manufactured in standard frame sizes. They also come in different enclosures to suit various environmental conditions and duties (eg drip-proof, splash-proof, and submersible).

All materials are subject to physical limitations, i.e. limits beyond which they no longer retain their desired physical characteristics. Proper design and use of machines (and indeed all apparatus) should ensure that none of the constituent materials exceeds its physical limitations under normal operating conditions.

To select an appropriate machine for his system, the user must know clearly the requirements of that application (eg speed, voltage, power, etc.), and the conditions under which the machine will be running. He will then be able to select the most economical machine that meets these requirements and conditions.

CHAPTER 3: ARMATURE WINDINGS

3.1

The coils on the armature are connected to each other and to the commutator segments to form what is called an 'armature winding'.

3.1 Coil details

Coil sides: active parts of coil; placed inside slots.

Coil span: separation between the two coil sides along the armature surface (i.e. the arc covered by the coil).

Full-pitched coil: coil span exactly equal to pole pitch.

Chorded or short-pitched coil: coil span slightly less (or possibly more) than an exact pole pitch.

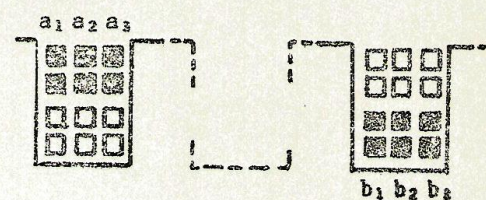
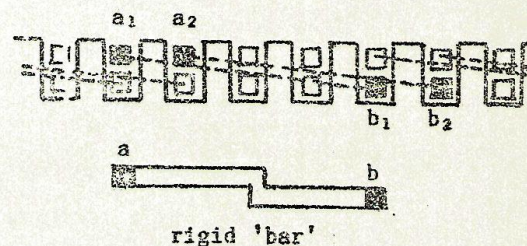
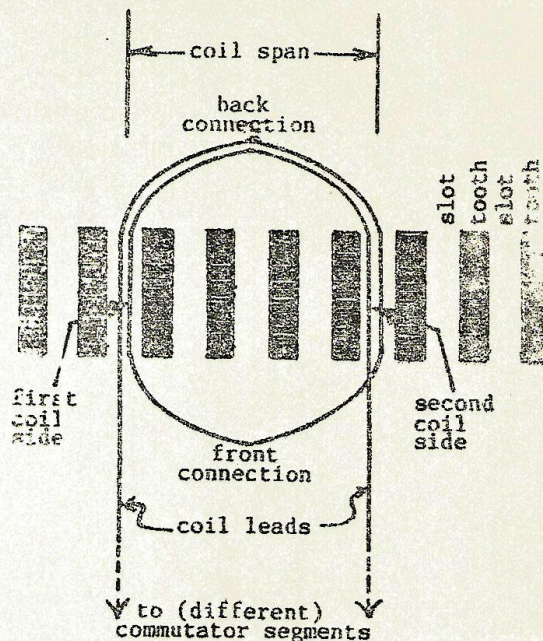
All sections of the coil are insulated: from each other, from adjacent coils, and from core iron. The level of insulation at any point is determined by the potential difference being insulated.

Coils designed for low voltage and high current have few turns of large sections; conversely, coils for high voltage and low current have many turns of small sections. Large machines have few turns/coil, possibly only one, made of preformed copper bars. Small machines' coils are made of many turns of flexible wire wound and bent to shape.

3.2 Two-layer windings

Machine windings are made in two layers: for each coil, one coil side is placed in the top half of its slot (top layer), and the second coil side is placed in the bottom half of its slot (bottom layer). This makes it easy to arrange end connections (front & back) in a regular manner; all coils are then identical so that the winding is symmetrical and compact.

There are at least two coil sides in each slot, one in top layer and one in bottom layer. In large machines, there may be 2, 3, 4, etc, coil sides per slot.



3 coil sides/slot/layer

2 turns/coil

⇒ $3 \times 2 = 6$ conductors/slot/layer

⇒ $2 \times 6 = 12$ conductors/slot

(also 6 coil sides/slot)

3.2

3.3 Some numbers

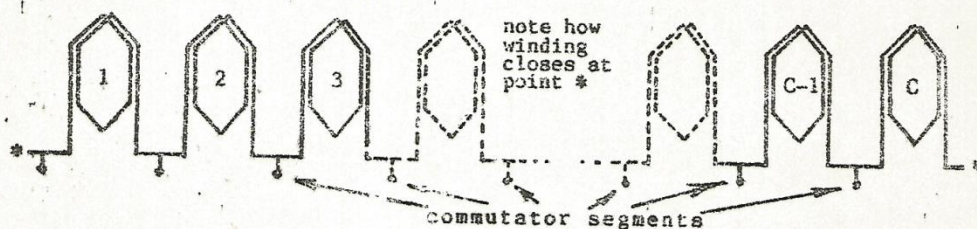
C = total number of coils on armature;
 N = number of turns in each coil;
 S = total number of slots in armature;
 Z = total number of armature conductors,
 $= 2NC$.

$\frac{S}{2P}$ = number of slots/pole,
 = pole pitch measured in slots.

NC = total number of loops;
 $2C = Z/N$ = total number of coil sides;
 $Z/S = 2NC/S$ = number of conductors/slot;
 $2C/S$ = number of coil sides/slot;
 NC/S = number of conductors/slot/layer;
 C/S = number of coil sides/slot/layer.

3.4 Interconnection of coils

All the coils on the armature are connected together to form a single closed circuit (called the armature winding): starting with any coil, its end is connected to the beginning of a second coil; the end of the second coil is connected to the beginning of a third coil, and so on. This is repeated until the last coil, C th coil, is reached; its end is connected to the beginning of the first coil, so that the circuit is closed. The interconnections between the coils are made on the commutator: the second lead of the first coil and the first lead of the second coil are soldered together on the riser of one commutator segment; the second lead of the second coil and the first lead of the third coil are soldered together on the riser of another commutator segment; finally, the second lead of the last (C th) coil and the first lead of the first coil are soldered to the riser of one commutator segment.



The above diagram shows only the general connection of coils to each other and to the commutator segments to form a closed winding. It does not show the relative positions of the coils around the armature, nor the actual locations of the commutator segments to which they are connected; the actual positions of coils and commutator segments will be explained in the following section. From the above diagram it should be clear that

total number of commutator segments = total number of coils = C .

3.5 Winding schemes

Armature coils may be interconnected according to one of two schemes, giving rise to two types of armature windings, lap and wave.

(In the winding diagrams below, a full line indicates a coil side lying in the top layer, and a dashed line indicates a coil side lying in the bottom layer. Arrows on coil sides may be taken to indicate direction of either induced emf or current.)

y_c = commutator pitch = number of commutator segments advanced from the first coil lead to the second (same for

all coils).

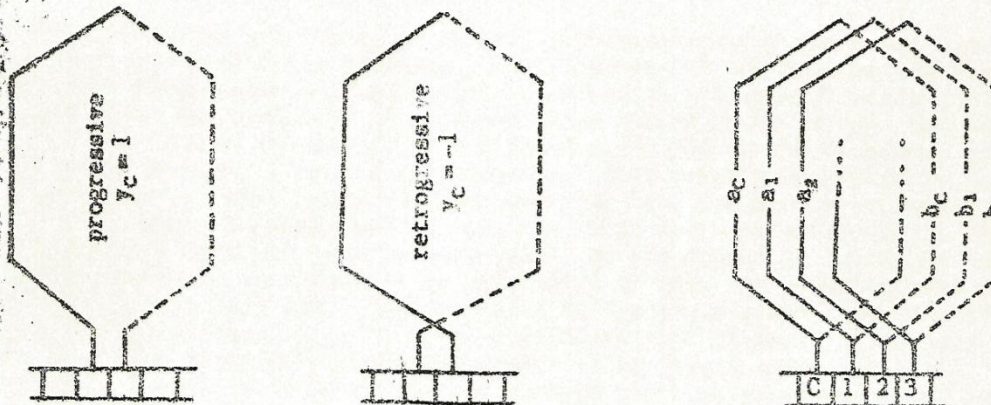
3.5.1 Lap winding

3.3

In lap windings, the two coil ends are connected to adjacent commutator segments; i.e. if the lead from side a is connected to commutator segment x , then the lead from side b is connected to segment $x+1$. Thus

$$y_c = \pm 1$$

The winding is continued until all coils are traversed up to the last coil C , which then closes on the first coil. A lap winding can be made to fit any number of coils and poles, C and $2p$. The choice of progressive or retrogressive windings has no significant effect.

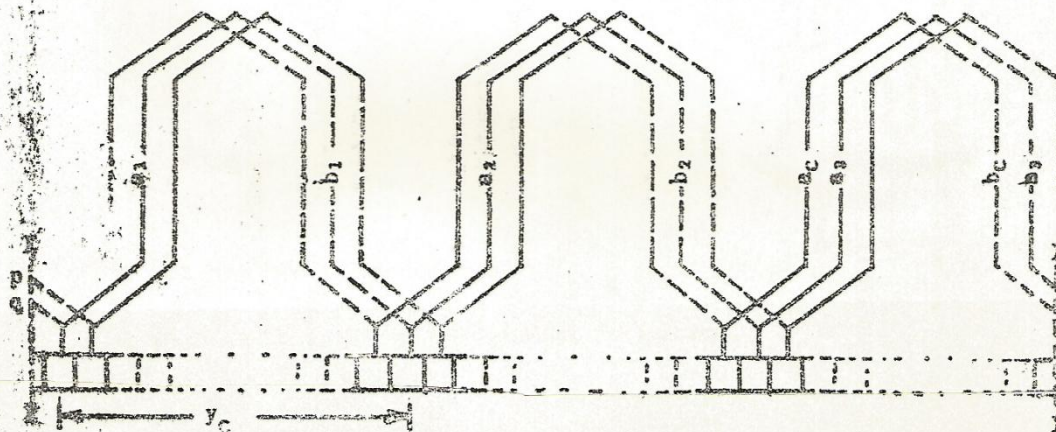


3.5.2 Wave winding

In wave windings, the two coil ends are connected to commutator segments that are approximately two pole pitches apart (where a pole pitch is now measured in number of segments or coils, i.e. $C/2p$). The commutator pitch is then

$$y_c = (C \pm 1)/p \quad \Rightarrow \quad C = py_c \pm 1$$

After traversing all pole pairs, the winding should return to a commutator segment adjacent to the initial one, either the one just after it (progressive as in the figure), or the one just before it (retrogressive). The winding is continued until all coils are traversed with the last coil closing on the first coil. Unlike the lap winding, the wave winding cannot be made to fit just any number of coils and poles: in the above equation, the values of C and p must be such that y_c turns out to be an integer. (If a wave winding is to be placed on an unsuitable armature, some coil positions must be left out; for mechanical balance, dummy coils are placed in these positions (dummy coils are not connected electrically)).



3.4

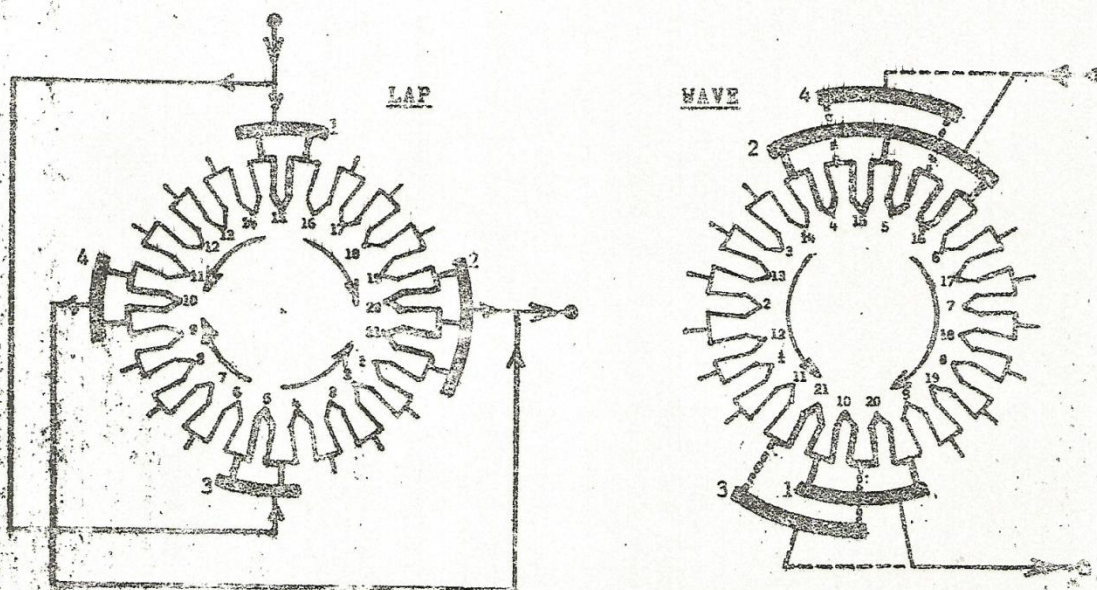
3.6 Example

Consider a 4-pole machine having 21 coils ($2p=4$, $p=2$, and $C=21$). In principle, such a machine can have 7 slots with 3 coil sides/slot/layer (i.e. 6 coil sides/slot), but it is more likely to have 21 slots with one coil side/slot/layer (2 coil sides/slot). Assuming the second case, the pole pitch is found to be $21/4 = 5\frac{1}{4}$ slots so that full-pitched coils cannot be used; we shall assume a coil span of 5 slots (although we could have chosen a coil span of 6 slots). The developed diagrams for progressive lap and wave windings are shown on page 3.5. The commutator pitch for the lap wdg is +1, while for the wave wdg it is

$$y_c = (C+1)/p = (21+1)/2 = 11$$

Coils, coil-side positions (or slots), and commutator segments are numbered sequentially around the armature. The locations of the 4 poles are also shown. The coil sides under each pole carry currents in the same direction, which is opposite to the direction of currents under the adjacent poles. The coils whose sides are located between poles are short-circuited by the brushes; they are indicated by heavy lines in the diagrams. Such coils are said to be 'undergoing commutation'; each one of them is emerging from a polar region where its current had a certain direction, and is about to enter the next polar region where its current will have the reverse direction; at the moment it is in the 'interpolar' region where the flux density is very small so that the instantaneous emf induced in the coil is very small (which serves to limit the short circuit current circulating between coil, commutator segments, and brush). It is very important to note that although the brushes appear to be placed under the poles, they are actually connected to coils passing through the interpolar region of small flux density (the q-axis, or the magnetically neutral axis, or the brush axis - see diagram on page 2.2). A careful study of the developed diagrams of page 3.5 should show that the coils are connected as in the sequence diagrams below.

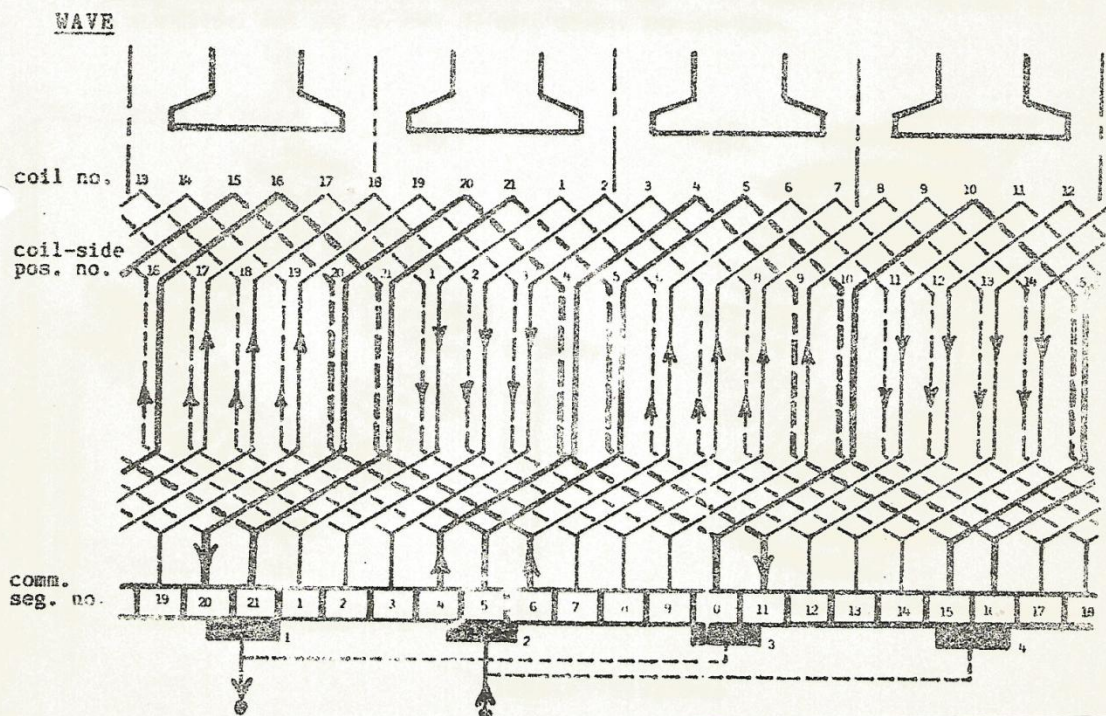
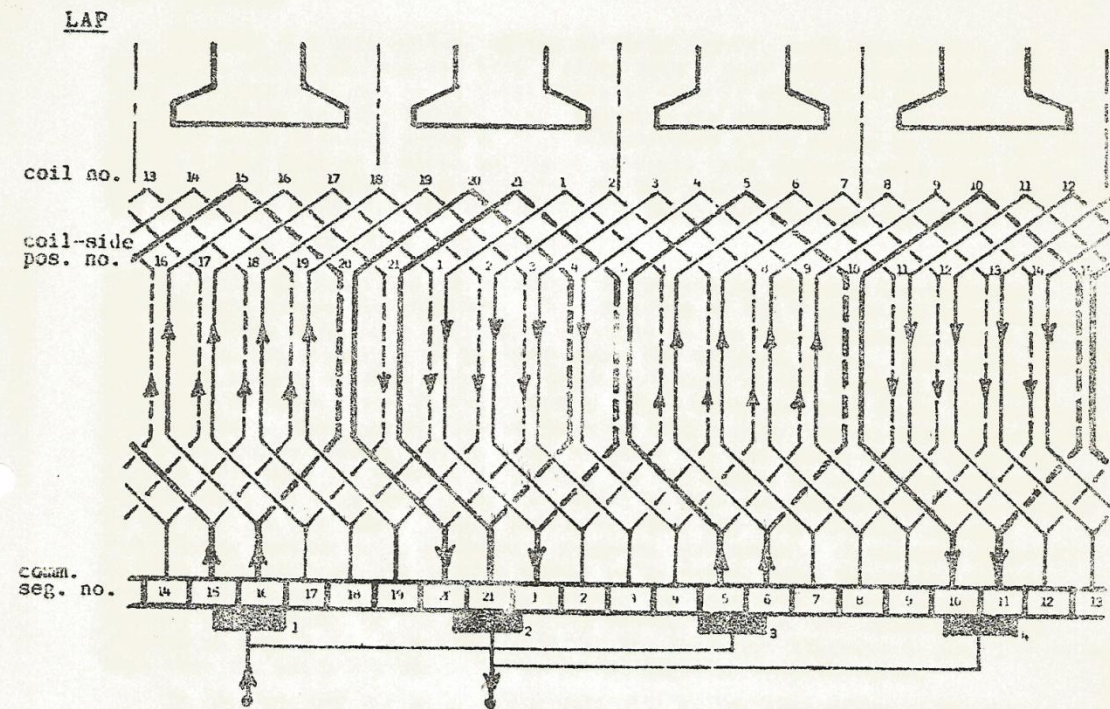
The current and emf at the terminals will be the same although the actual coils between brushes are changing all the time. The commutator and brushes force a stationary emf and current pattern around the armature.



Sequence diagrams.

Developed diagrams.

3.5

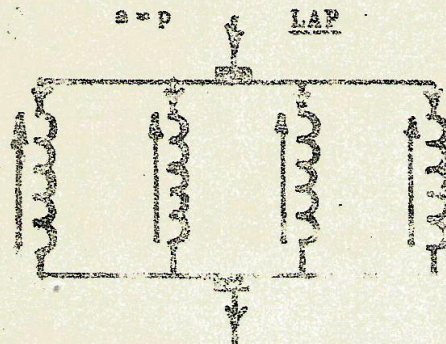


3.7 Parallel paths

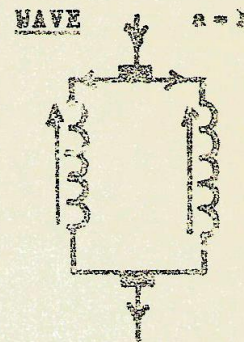
3.6

From the diagrams of pages 3.4 and 3.5, it will be seen that the armature coils form a closed winding that is tapped by the brushes at certain points. In effect, the brushes divide the winding into a number of parallel paths each of which is composed of a number of coils in series. The terminal current is divided among the parallel paths. At any moment during operation, there are some short-circuited coils; these are not included in the paths. The circuit diagrams for the lap and wave windings are shown below. In each case, the terminal voltage is equal to the voltage of the individual parallel paths.

From the sequence diagram for the lap wdg on page 3.4, it will be seen that all the brushes are necessary: if any brush is removed, there will be opposing



$2a$ = number of parallel paths;
 a = number of pairs of parallel paths.



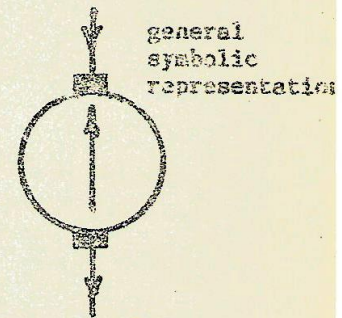
emf's in series (which would cancel out). Thus the number of brushes is equal to the number of poles, and hence the number of parallel paths is also equal to the number of poles:

$$\text{lap wdg: } 2a = 2p, \quad a = p.$$

From the sequence diagram for the wave wdg, on the other hand, it will be seen that only two brushes are really necessary: alternate brushes are connected to each other internally through short-circuited coils. Thus brushes 3 and 4 may be disconnected and removed without affecting induced emf's and currents. In other words, the brushes divide the wdg into two parallel paths only:

$$\text{wave wdg: } 2a = 2, \quad a = 1.$$

The extra brushes may be removed, but in practice they are sometimes kept to obtain better current distribution over the commutator.



3.8 Comparison of lap and wave windings

A lap wdg has $2p$ parallel paths and must have $2p$ brushes (or brush groups). A wave wdg has two parallel paths and requires only two brushes (or brush groups), but it can have $2p$ brushes.

A lap wdg can be made to fit any number of coils and poles. A wave wdg can be fitted only if the numbers of coils and poles yield an integer commutator pitch $y_c = (C \pm 1)/p$.

A brush on a lap wdg generally short-circuits one coil during commutation. In a wave wdg having only two brushes, each brush short-circuits p coils in series; in a wave wdg having $2p$ brushes, a coil is short-circuited by two

brushes in series.

3.7

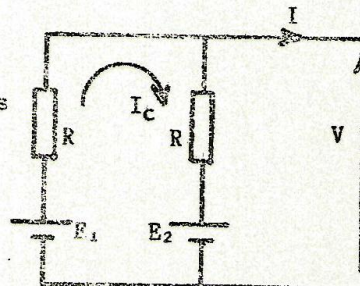
Assume now that a given wdg can be connected in either lap or wave. The coil emf and current are the same in both cases. The lap-connected wdg will have a high terminal current and a low terminal voltage, while the wave-connected wdg will have a low terminal current and a high terminal voltage (for $2p \geq 4$). The two wdg's will have the same power.

Conversely, assume a machine is to have a specified terminal voltage and a specified terminal current. If it is connected in lap, it will have a low current per coil, and a high voltage per coil; therefore each coil will have many turns of small cross-section, and a higher level of insulation is needed. If it is connected in wave, it will have a high current per coil and a low voltage per coil; therefore the coils will have relatively few turns and large sections, and a relatively lower level of insulation is needed. In this respect, wave wdg's are better than lap wdg's because they allow for better cooling of wdg's, and because they have higher space factors (space factor = copper area/total slot area). In general, wave wdg's are used in almost all machines up to 50 KW, and in all high voltage machines. Lap wdg's are used mostly in large machines having low voltage/high current ratings.

3.9 Equalizers

In lap wdg's, each path is associated with a pair of poles. Thus if there is asymmetry in the magnetic circuit (due to wear of bearings, or eccentricity of shaft), the emf's induced in the paths will not all be exactly equal to each other. Unequal emf's connected in parallel give rise to circulating currents that can be quite large, causing heavy and unnecessary heating.

To reduce this effect, points that should have the same voltage are connected to each other by means of equalizers (or equalizing connections, or equalizing rings). Such points are located two pole pitches apart. Each equalizing ring is connected to p points in alternate paths.



Circulating current:

At no load, $I = 0$
and

$$I_c = \frac{E_1 - E_2}{2R}$$

If $E_1 \neq E_2$, then $I_c \neq 0$ and the wdg's will heat up due to copper loss even with the machine unloaded.

In the wave wdg, there are only two paths through the armature. The coils of each path are distributed uniformly around the armature, and hence cover all pole pairs. Any asymmetry in the magnetic circuit will have the same effect on both paths, so that the two induced emf's will be identical. Thus wave wdg's do not require equalizers, which is another advantage of wave wdg's.

3.10 Multiplex windings

The lap and wave wdg's described so far are called simple or simplex wdg's. Duplex wdg's are composed of two simplex wdg's interleaved around the armature, and connected so as to have twice as many parallel paths:

$$\text{duplex lap wdg: } 2a = 4p \\ a = 2p$$

$$\text{duplex wave wdg: } 2a = 4 \\ a = 2$$

Similarly, there may be triplex wdg's, and so on. Such multiplex wdg's are rarely used.

3.11 Armature calculations

3.6

Consider a symmetrical wdg composed of $2a$ identical parallel paths. It has

$C/2a$ coils/path,

C/a coil sides/path,

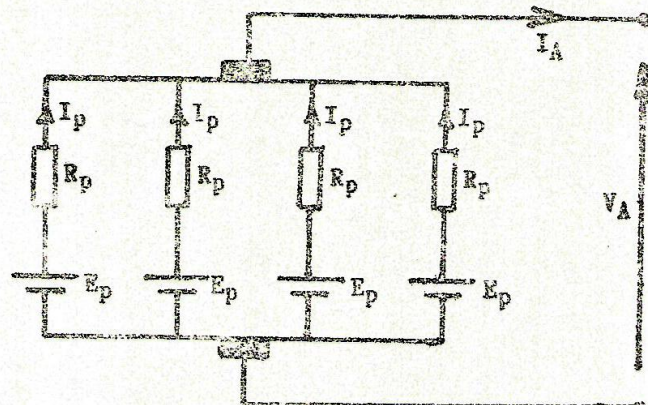
$Z/2a = NC/a$ conductors/path.

Let

E_p = induced emf in each path;

I_p = current flowing through each path;

R_p = resistance of each path.



Circuit representation of armature winding.

Also let

V_A = armature terminal voltage;

I_A = armature terminal current;

E_A = armature emf = Thevenin equivalent emf for armature winding;

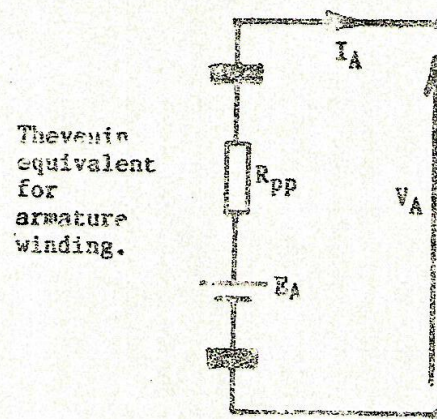
R_{pp} = Thevenin equivalent resistance for armature winding;

R_A = total effective armature resistance.

Applying KVL:

generator: $V_A = E_A - I_A R_A$,

motor: $V_A = E_A + I_A R_A$.



Thevenin equivalent for armature winding.

3.11.1 Armature resistance

Single loop: $R_{loop} = \frac{\rho l_m}{A}$,

where ρ = resistivity of copper at the working temperature;

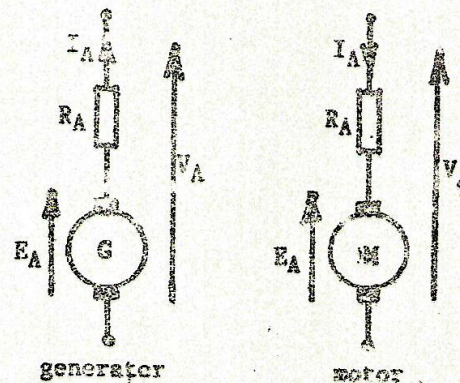
l_m = mean length of a single loop;

A = cross-sectional area of the conductor.

Coil: $R_{coil} = N^2 R_{loop} = \frac{N^2 \rho l_m}{A}$.

Path: $R_p = \frac{C}{2a} R_{coil} = \frac{NC \rho l_m}{2a A} = \frac{Z \rho l_m}{4a A}$.

Winding: $R_{pp} = \frac{1}{2a} R_p = \frac{1}{4a^2} \frac{Z \rho l_m}{A} = \frac{Z \rho l_m}{8a^2 A}$.



generator

motor

Common symbolic representation of armature winding.

Effective armature resistance: $R_A = R_{pp} + R_{brushes} + R_{contact}$;

$R_{brushes}$ is the resistance of the carbon brushes. $R_{contact}$ is the resistance of the brush/commutator contact surface; it is nonlinear, and is usually taken as equivalent to a constant volt drop (for example 1 volt).

3.11.2 Armature emf

3.9

The average coil emf derived in section 1.9 is the same for all armature coils. Thus, for each path

$$E_p = \frac{C}{2a} \times E_{\text{coil}} = \frac{2pCN}{a} n\phi$$

But all paths are in parallel with each other, so that the armature emf is equal to the individual path emf's:

$$E_A = E_p = \frac{2pCN}{a} n\phi = k_e n\phi \quad (k_e = \frac{2pCN}{a} = \frac{Zp}{a})$$

An alternative expression can be obtained in terms of $\omega_r (= 2\pi n)$:

$$E_A = (k_e/2\pi) \omega_r \phi = k \omega_r \phi \quad (k = k_e/2\pi = \frac{pCN}{\pi a} = \frac{Zp}{2\pi a})$$

3.11.3 Torque

According to KCL, the terminal current I_A is the sum of all path currents:

$$I_A = 2a \times I_p \quad \rightarrow \quad I_p = I_A/2a$$

A path is composed of coils in series, so that the path current I_p flows through the individual coils:

$$I_{\text{coil}} = I_p$$

The average coil torque was derived in section 1.10:

$$T_{\text{coil}} = \frac{2p}{\pi} N I_{\text{coil}} \phi = \frac{2p}{\pi} N I_p \phi = \frac{pN}{\pi a} I_A \phi$$

The total armature torque is the sum of all coil torques acting in the same direction and aiding each other:

$$T = C \times T_{\text{coil}} = \frac{pCN}{\pi a} I_A \phi = k I_A \phi \quad (k = \frac{pCN}{\pi a} = \frac{Zp}{2\pi a} \text{ as before})$$

3.11.4 Conversion power

The conversion power corresponding to electromechanical energy conversion in the machine is given by:

$$\text{on the electrical side: } P_c = E_A I_A$$

$$\text{on the mechanical side: } P_c = \omega_r T$$

Note that

$$P_c = E_A I_A = (k \omega_r \phi) I_A = (k I_A \phi) \omega_r = \omega_r T$$

Using P_{in} to denote input power to the armature, and P_{out} to denote output power from the armature, we have:

$$\text{generator: } P_{\text{in}} = \omega_r T = P_c, \quad P_{\text{out}} = V_A I_A = E_A I_A - I_A^2 R_A = P_c - P_{\text{Cu}};$$

$$\text{motor: } P_{\text{in}} = V_A I_A = E_A I_A + I_A^2 R_A = P_c + P_{\text{Cu}}, \quad P_{\text{out}} = \omega_r T = P_c.$$

P_{Cu} is the total copper loss (or ohmic loss) in the armature

CHAPTER 4 : THE MAIN FIELD

The operation of dc machines is based on the interaction between the armature conductors and the air-gap field, which results in induced emf and developed torque. In chapter 3 we studied armature windings, and we now study the field. In this chapter we study the main field, which is the field produced by the field coils (or PM's) on the stator. In the next chapter we shall study armature reaction, which is the field produced by armature conductors.

To be able to study the main field by itself, in this chapter we shall assume that there is no armature current, i.e. the machine is operating at no-load.

4.1 Main Field Distribution

If the field coils act alone (i.e. no current in armature conductors), the flux in the dc machine will have the general pattern shown in fig. 4.1. Most of the flux in the pole cores crosses the air-gap to link the armature windings; this is the useful flux per pole Φ . However, some of the flux lines complete their paths without linking the armature wdg; this is the leakage flux (in actual machines, the leakage flux is much less than shown in fig. 4.1).

The useful flux Φ is produced by the mmf of the field coils. The mmf per pole M_F is the sum of the mmf's of all coils placed on one pole (which may be one, or two, or more - see section 4.2). Thus

$$M_F = \sum N_F I_F \text{ Ampere-turns/pole}$$

If you follow the lines of the useful flux in fig. 4.1, you will find that the path of the useful flux is composed of the following parts in series : stator yoke, pole core, pole shoes, air-gap, armature teeth, and armature core. As a series circuit, the over-all reluctance is dominated by the highest reluctances in the path, which are (a) the air-gap, and (b) armature teeth (when saturated).

While fig. 4.1 shows the flux distribution all over the machine, fig. 4.2 shows the flux density distribution in the air-gap, i.e. the effective field seen by the armature conductors. The curve is smooth if the armature surface is assumed to be smooth; in fact, armature slots introduce a ripple that moves along the curve as the armature rotates; we shall neglect the slotting effect. A much more serious distortion of the main field is caused by armature reaction, which we shall study in chapter 5.

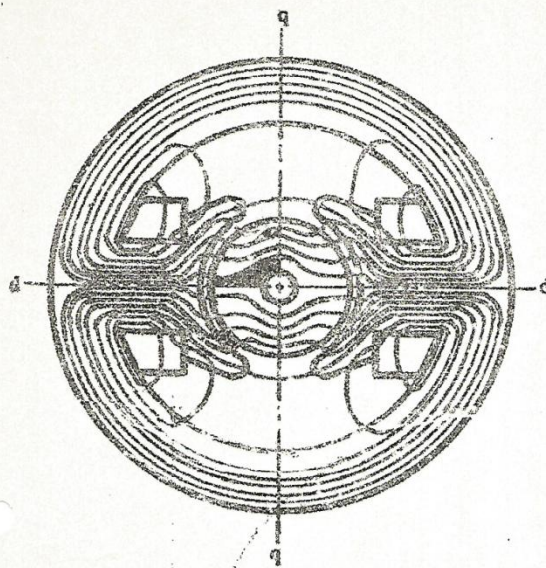


Fig. 4.1 Rough sketch of main field flux distribution in a dc machine. Leakage flux greatly exaggerated.

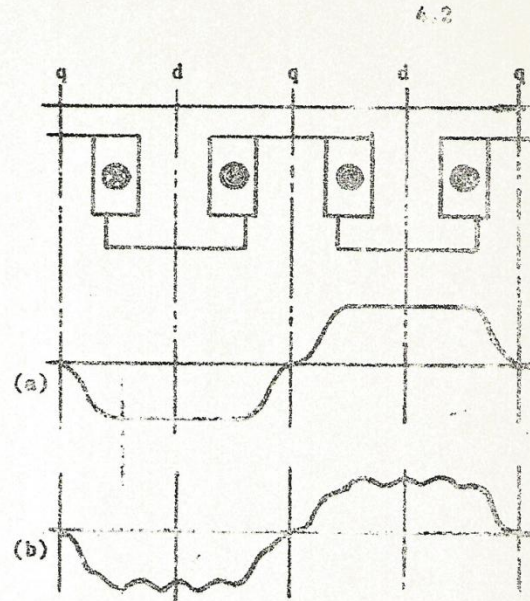


Fig. 4.2 Air-gap flux density distribution due to main field:
(a) effect of armature slots neglected;
(b) slotting effect shown.

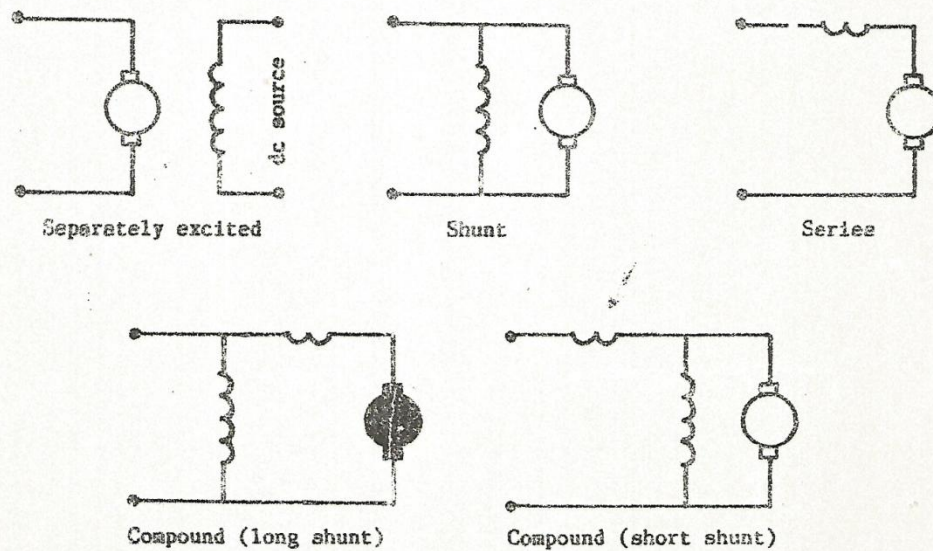


Fig. 4.3 Methods of field excitation for dc machines.

4.2 Field excitation

The main field may be produced by means of permanent magnets (PMDC), or by means of coils placed on the poles (wound-pole). PM's are compact (small size), require no supply for the field, and are economical in operation (no Ohmic losses); however, they are very expensive. Wound-pole machines are much cheaper, and allow control of the field; they are much more commonly used.

Field coils in wound-pole machines may be connected in various ways - see fig. 4.3. They may be divided as follows :

Separately-excited : field coils supplied from separate source.

Self-excited : field coils are connected with the armature. They may be in parallel (shunt field), or in series. Compound machines have both shunt and series fields.

Shunt field coils are made of many turns of thin wire; they are designed to carry a current much smaller (less than 10 %) than the armature current I_A . The shunt field current may be controlled by connecting a variable resistor (rheostat) in series with the coils.

Series field coils are made of just a few turns of thick wire; they carry the armature current I_A (in short-shunt compound machines, the series field current differs from the armature current by an amount equal to the shunt field current, which is small). The series field current may be controlled by placing a variable resistor in parallel with the coils.

Compound machines may be connected in long-shunt or in short-shunt (see fig. 4.3); there is no major difference between the two types of connection. The shunt and series coils may produce fields that aid each other, and the compounding is said to be cumulative; conversely, the shunt and series fields may oppose each other, and the compounding is then said to be differential. In general, the shunt field is substantially greater than the series field, and hence dominates.

From the above, it should be clear that the resistance of shunt field coils is quite large, while that of series field coils is quite small. Moreover, control of the field current results in control of the induced emf, and hence control of general machine operation; this will be studied in detail in later chapters.

Some special-purpose dc machines have more than two sets of field coils; each set of coils is fed from a different controlling signal, so that motor operation is determined by the over-all combination of controlling signals. Such motors are commonly used in control applications.

applications .

4.3 The magnetization curve

In wound-pole machines, the flux is produced by the field excitation, i.e. by the mmf of the field coils. The magnetization curve is the relationship between the flux per pole ϕ and the mmf per pole M_f producing it, fig. 4.4.

M_f is applied to a magnetic circuit composed of the air-gap reluctance in series with the reluctance of iron parts (assuming the leakage flux is negligible). The air-gap reluctance is constant, but the reluctance of iron parts increases as they enter into saturation. At low excitation (say M_{f1}), the iron is unsaturated so that its permeability is very high, and its reluctance is negligible relative to that of the air-gap; the mmf drop in the iron is negligible, and practically all the applied mmf M_{f1} is taken up in driving the flux ϕ_1 across the air-gap. At higher excitation (say M_{f2}), iron parts begin to saturate so that their permeability goes down and their reluctance goes up; the mmf drop in the iron is no longer negligible relative to the mmf drop in the air-gap. The applied mmf M_{f2} divides between the air-gap and the iron according to the ratio of their reluctances (similar to voltage division in electric circuits). As the excitation is increased further (to, say, M_{f3}), the iron parts are driven further into saturation so that they consume a larger proportion of the applied mmf M_{f3} ; indeed, the mmf drop in iron may become greater than the mmf drop in the air-gap. Armature teeth saturate first, followed by the poles, and then the armature core and yoke.

The relationship between the flux per pole ϕ and the mmf drop in the air-gap (which is less than M_f) is linear; it is represented by the air-gap line in fig. 4.4. At low excitation, the magnetization curve follows the air-gap line. As excitation increases, the machine begins to saturate, and the curve moves away from the line (knee of the curve). At heavy excitation, the machine is well into saturation, and the curve is well away from the line. It is noted that at zero field excitation ($M_f = 0$), there is some remanent magnetism (due to hysteresis in the iron) so that the flux ϕ is not zero.

Now, from chapter 3, we have

$$E_A = k_e n \phi = k \omega_r \phi \quad \text{and} \quad T = k I_A \phi$$

where k_e and k are constants depending on machine parameters. If ϕ is known, then E_A may be computed for a given n , and T may be computed for a given I_A . However, if it is the field excitation M_f that is known, we must first find ϕ from the magnetization curve; the procedure is

Graphical because there is no ready formula giving ϕ in terms of M_f .

4.5

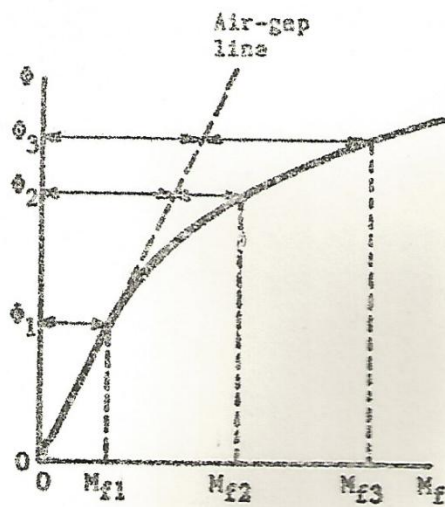


Fig. 4.4 Magnetization curve, ϕ vs. M_f .

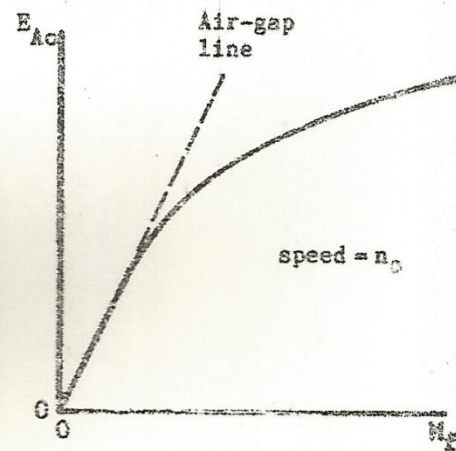


Fig. 4.5 Magnetization curve, E_{Ao} vs. M_f ($n=n_0$).

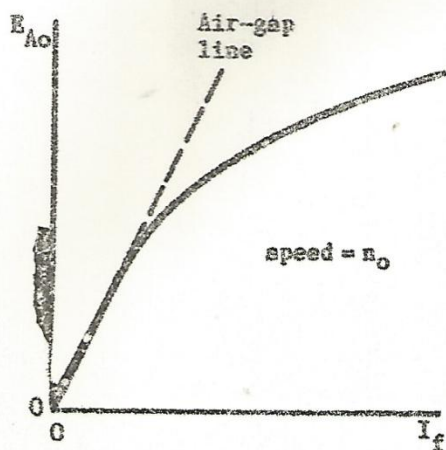


Fig. 4.6 Magnetization curve, E_{Ao} vs. I_f (open circuit characteristic - OCC).

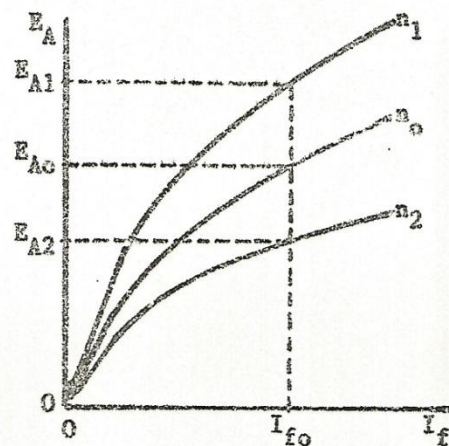


Fig. 4.7 OCC at different speeds, $n_1 > n_0 > n_2$.

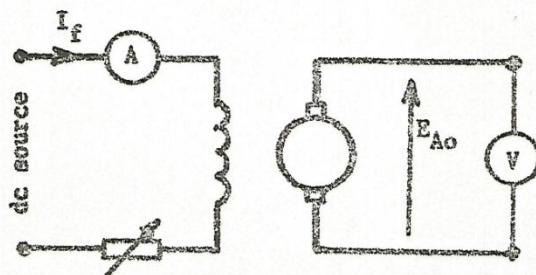


Fig. 4.8 Test to measure OCC; machine driven at constant speed n_0 .

At a given constant speed n_0 ,

$$E_{Ao} = k_e n_0 \phi = k_o \phi$$

so that the vertical axis of the magnetization curve may be scaled in terms of E_{Ao} instead of ϕ ; this is shown in fig. 4.5. If, moreover, only one field winding (i.e. one set of field coils) is excited, then

$$M_f = N_f I_f$$

where N_f and I_f correspond to the wdg excited; since N_f is constant, the horizontal axis of the magnetization curve may be scaled in terms of I_f instead of M_f . This last form of the magnetization curve, shown in fig. 4.6, can be obtained experimentally by the simple test shown in fig. 4.8: the machine is driven at constant speed n_0 ; the field current I_f is varied, and the corresponding values of emf E_{Ao} are recorded. If the test is performed at rated speed, the resulting magnetization curve is called the open circuit characteristic (OCC).

To obtain the magnetization curve at different speeds as in fig. 4.7, we need perform the (open circuit) test only once at, say, n_0 ; at a given value of field current, say I_{f0} , we have

$$E_{A1} = k_e n_1 \phi = k_e n_0 \phi (n_1/n_0) = E_{Ao} (n_1/n_0)$$

Thus the emf values at n_1 are obtained by multiplying the corresponding emf values at n_0 by the speed ratio (n_1/n_0).

If the OCC is available, the magnetization curve E_A vs. M_f may be obtained if N_f is known, and the magnetization curve ϕ vs. M_f may be obtained if k_o or k is known.

Exercise The OCC of a dc machine running at 300 rpm is given in the adjacent table. Plot it.
 (a) On the same graph, plot the curves at 600 rpm and at 1000 rpm. (b) If each field coil has 630 turns, plot the magnetization curves E_A vs. M_f . (c) If the machine is wave wound with 6 poles, and has 46 armature coils of 3 turns each, plot the magnetization curve as ϕ vs. M_f . (d) At 800 rpm, estimate the mmf drops in the air-gap and in the iron when the emf is 50, 100, 150, 200, 250, and 300 volts. (e) What is the residual (or remanent) flux per pole? (f) What is the induced emf when the field current is 5.5 A and the speed is 1500 rpm?

I_f amps	E_A volts
0	8
0.3	28
0.5	46
1.0	94.5
1.5	143
2.0	175
2.5	195.5
3.0	211
3.5	224
4.0	234.5
4.5	243.5
5.0	251.5
6.0	265.5
7.0	276.5
8.0	283
9.0	284.5
10.0	302

CHAPTER 5 : ARMATURE REACTION

5.1

In chapter 4 we studied the field produced by the field coils acting alone. But when a machine is loaded, currents will flow in the armature coils, and an armature field is set up. This armature reaction distorts the field distribution in the machine, and results in some adverse effects that must be treated for satisfactory operation. In this chapter, we study armature reaction and its effects.

5.1 Armature field

When the machine is loaded, current flows in the armature conductors, and tends to set up a magnetic field as shown in fig. 5.1. The armature may be viewed as a single coil acting in the q-axis; most of the flux follows the path composed of : arm teeth, air-gap, pole shoes, and arm core. Note in particular that the arm field is perpendicular to the main field shown in fig. 4.1 and repeated here in fig. 5.3, which acts in the d-axis. The armature mmf is distributed along the air-gap as shown in fig. 5.2 (with the actual slots approximated by a continuous belt of current). The arm mmf M_a peaks at the q-axis and is zero at the d-axis; its peak value is

$$M_{am} = \frac{1}{2} \cdot \frac{Z}{2p} \cdot \frac{I_A}{2a} = \frac{Z}{8pa} I_A = \frac{NC}{4pa} I_A$$

The arm mmf tends to set up the air-gap flux density distribution shown in fig. 5.2; although the mmf is maximum at the q-axis, the flux density is seen to fall because of the large reluctance there resulting from the long air path.

5.2 Resultant field

Fig. 5.1 shows the arm field by itself, while fig. 5.3 shows the main field by itself. Note that the main field acts along the d-axis, while the arm field acts along the q-axis. In the arm core and pole shoes, the two fields are perpendicular to each other. In the air-gap, however, the arm field aids the main field over a half pole-pitch, and opposes it over the next half pole-pitch. Superposition of the two fields yields the resultant flux distribution shown in fig. 5.4; this is the actual distribution in the machine when both armature and main fields are present, i.e. both arm and field wdgs are excited. Note how armature reaction has distorted the field distribution; note, in particular, how the magnetic neutral axis is now shifted from the q-axis (or mechanical neutral axis, or brush axis). The air-gap flux density is strengthened under one pole tip, and weakened under the next

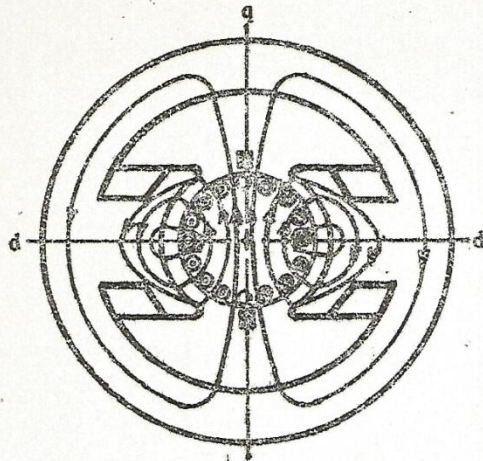


Fig. 5.1 Flux distribution due to armature alone.

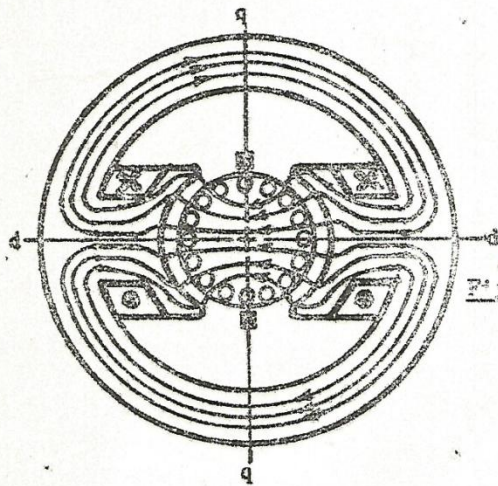


Fig. 5.3 Flux distribution due to main field alone.

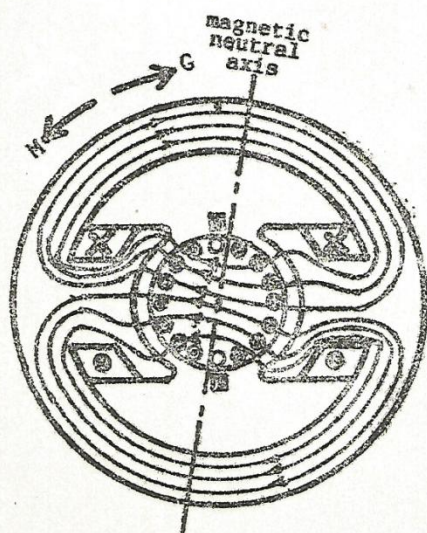


Fig. 5.4 Resultant flux distribution.

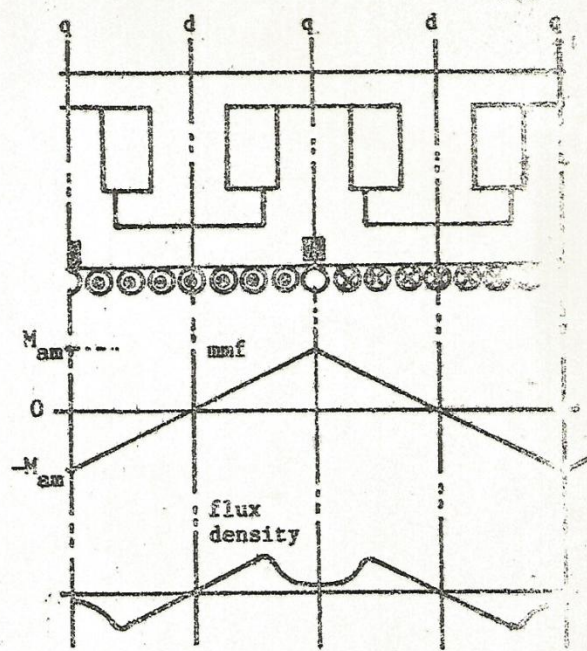


Fig. 5.2 Armature mmf and air-gap density distribution due to armature alone (slotting effects neglected).

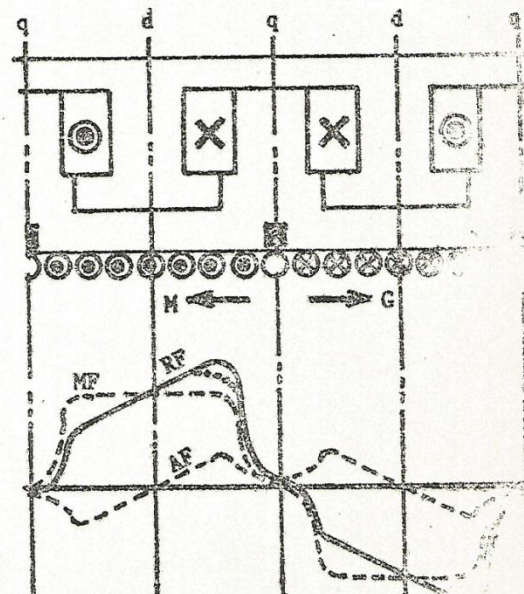


Fig. 5.5 Air-gap flux density distribution.
MF = main field;
AF = armature field;
RF = resultant field.

pole tip, as shown in fig. 5.5. The zero-crossing of the flux density wave is now shifted from the q-axis.

The directions of main field and arm currents in fig. 5.4 correspond to (a) generator operation for CW arm rotation, or to (b) motor operation for CCW arm rotation; this is easily verified by noting that the torque on the arm conductors is CCW. It is thus seen, from fig. 5.4 or 5.5, that the flux is "pulled" in the direction of rotation for generator operation, and in the direction opposite to rotation for motor operation; thus the shift in the magnetic neutral axis is in the direction of rotation for generator operation, and in the direction opposite to rotation for motor operation.

5.3 Demagnetizing effect

The arm reaction acts on the q-axis and is therefore generally perpendicular to (or "in quadrature with") the main field which acts on the d-axis; it is thus called "cross-magnetizing" armature reaction. For a linear magnetic circuit, the cross-mag arm reaction has no effect on ϕ , the useful flux per pole: the arm mmf in one half pole-pitch is equal and opposite to the arm mmf in the other half; therefore it adds and subtracts equal amounts to the main flux which thus remains unchanged. It follows that the average emf $E_A = k\omega_p\phi$ and the average torque $T = kI_A\phi$ are unaffected by cross-mag AR because ϕ itself is unaffected. However, because of the distortion of the air-gap flux density, fig. 5.5, the instantaneous emf and torque are no longer the same for all conductors under the pole face.

But the magnetic circuit is actually nonlinear because it includes iron parts which tend to saturate at high fields. In the half pole-pitch where the arm mmf aids the main field, the iron parts (arm teeth and pole tips) are driven deeply into saturation so that the increase in flux density there is less than the decrease in flux density in the other half pole pitch (where arm mmf opposes main field so that iron parts are driven down the knee of the mag curve into the linear part). This means that the peaks of the distorted flux density wave are chipped off as shown by dotted curves in fig. 5.5. It also means that there is a net decrease in ϕ ; i.e. cross-magnetizing AR has a demagnetizing effect. The decrease in ϕ results in reduction of the average emf E_A and average torque T .

Clearly, then, the effective magnetization curve on load ($I_A > 0$) lies somewhat below the OCC ($I_A = 0$), and is lower for higher armature

currents; see fig. 5.6. The curves merge with the OCC at the air-gap line because there is no saturation at low excitation.

The reduction in the useful flux due to AR is a nonlinear function of both field and armature mmf's, and hence of field and armature currents, I_F and I_A . The demagnetizing effect of AR may be represented as a reduction in induced emf, ΔE , or as a reduction in effective field current, ΔI_F ; see fig. 5.7. At a field current I_F and zero arm current $I_A = 0$, we have

$$\begin{aligned} \text{from fig. 5.3: } V_A &= E_A & \text{and from fig. 5.7: } E_A &= E_{Aoc} \\ \Rightarrow V_A &= E_A = E_{Aoc} \end{aligned}$$

At the same field current I_F , but with an on-load arm current $I_A \neq 0$, we have

$$\begin{aligned} \text{from fig. 5.3: } V_A &= E_A \pm I_A R_A & \text{and from fig. 5.7: } E_A &= E_{Aoc} - \Delta E \\ \Rightarrow V_A &= (E_{Aoc} - \Delta E) \pm I_A R_A = E_{Aoc} \pm (I_A R_A \mp \Delta E) \end{aligned}$$

Thus we may view E_{Aoc} as the induced emf, and ΔE as a voltage drop that subtracts from the arm resistance drop $I_A R_A$ for motor operation, and adds to it for generator operation. Alternatively, we might view AR as a reduction in effective field mmf: at a field current I_F and an arm current I_A , the effective field current is

$$I_F' = I_F - \Delta I_F$$

On the OCC, I_F' gives the actual induced emf E_A , while I_F gives the emf E_{Aoc} which would be induced when the load is removed (OC: $I_A = 0$).

Exercise The dc machine whose OCC is given on page 4.6 has a wdg resistance of $75 \text{ m}\Omega$ and a constant brush contact drop of 1.5 V . The mag curves at different armature loadings and constant speed 800 rpm are listed in the adjacent table. Plot these curves, together with the OCC, over the field current range shown here.

I_F amps	E_A volts		
	$I_A=100\text{A}$	$I_A=80\text{A}$	$I_A=60\text{A}$
3.5	217	210	221
4.0	225.5	223	230.5
4.5	232.5	235.5	238.5
5.0	239.5	243	246.5
6.0	252	256	260
7.0	262.5	267	271.5
8.0	270.5	275.5	280.5
9.0	277	283	288.5
10.0	283	290	296

(a) Determine ΔE and ΔI_F when the arm current is 80 A and the field current is 8 A . (b) Determine the terminal voltage when the field current is 7 A and the arm current is 60 A , and the machine is operating as a generator. (c) Repeat part b for motor operation. (d) If the machine is operating as a generator with terminal voltage 260 V and arm current 100 A , find E_A , E_{Aoc} , I_F , I_F' , ΔE , and ΔI_F . (e) Repeat part d for motor operation.

I_F' , ΔE , and ΔI_F . (e) Repeat part d for motor operation.

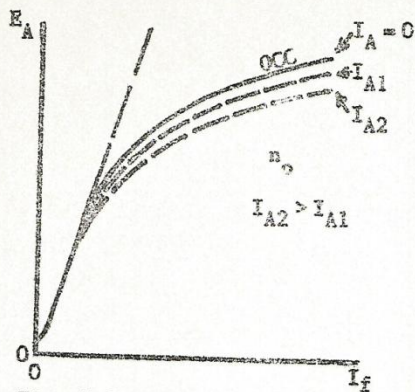


Fig. 5.6 Effect of load on magnetization curve.

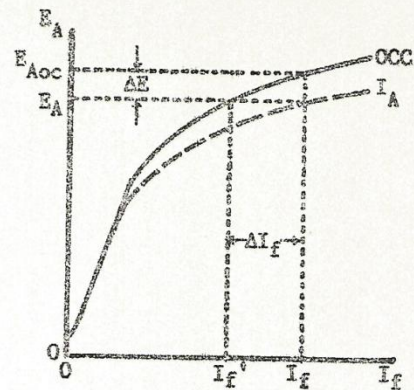


Fig. 5.7 Representation of demagnetizing effect of armature reaction.

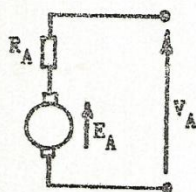


Fig. 5.8

$$V_A = E_A \pm I_A R_A$$

Fig. 5.9

Methods of increasing reluctance at pole tips.

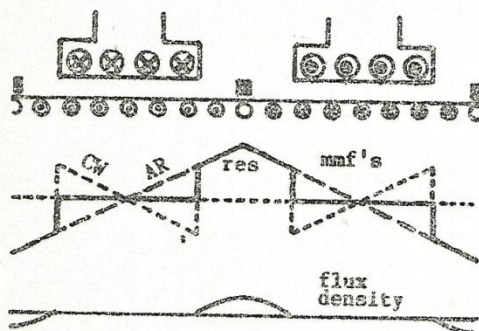
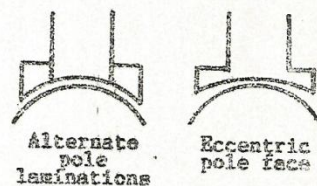


Fig. 5.10 Compensating effect of pole-face winding (compensating winding).

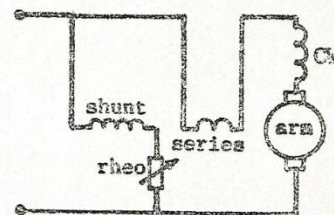
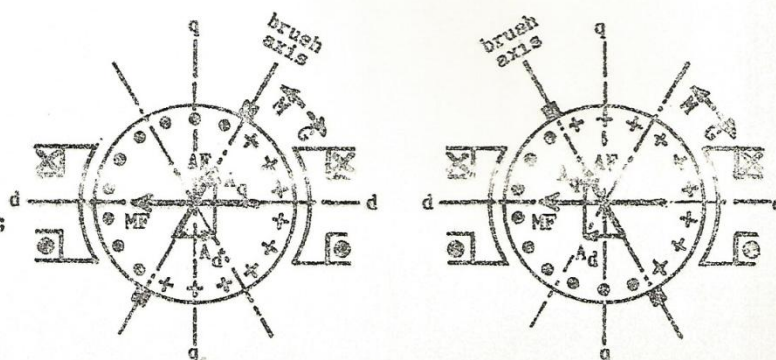


Fig. 5.11 Connection diagram of dc machine including compensating winding.

Fig. 5.12

Effects of brush shift.

MF = main field;
AF = armature field;
 A_d & A_q = direct and quadrature components of armature field.



5.4 Effects of armature reaction

The distortion of the field due to AR has a number of adverse (bad) effects :

- (1) Demagnetizing effect as discussed in section 5.3 : as arm current increases, the useful flux per pole decreases, and hence the induced emf and developed torque decrease.
- (2) Shift of the magnetic neutral axis from the brush axis means that coil sides of coils undergoing commutation are subjected to nonzero flux density, so that a nonzero emf is induced in them.
- (3) AR concentrates the flux at one pole tip, fig. 5.5. Although the average emf is approximately the same (slightly reduced - fig. 5.6), the instantaneous emf is increased for coils whose sides are passing under these tips; the increase can be quite large, especially if the machine is overloaded (large I_A). These coils are connected to commutator segments that are near the brushes where the air is highly ionised due to normal sparking. High inter-segment voltage applied to ionised air can cause breakdown of the air (arcing between segments). This may cause further ionisation and further arcing; in severe cases it may result in total flashover from brush to brush. The heat from the arc can damage the brushes and melt holes in the commutator.

Clearly, then, AR can have serious consequences that limit the operational conditions of the machine. The design and construction of the machine must therefore aim at reducing armature reaction :

- (1) Machines are designed to have a strong main field so that relative distortion due to AR remains small.
- (2) The machine is designed to have a high reluctance in the path of the armature cross-flux (arm teeth, air-gap, pole shoes - see fig. 5.1). This may be done by constructing poles with alternate laminations as in fig. 5.2 : with the amount of iron in the pole tips reduced, the flux density is increased, and the tips are driven quickly into saturation, and hence high reluctance. Alternatively, the air-gap under pole tips is made longer by using poles with eccentric pole faces as in fig. 5.9 (or chamfered faces). The increased reluctance also reduces the main flux, but the reduction is much smaller than the reduction in the armature cross-flux.

5.7

- (3) To avoid flashover, the instantaneous voltage between commutator segments must not exceed 30-40 volts. Machines are therefore designed to have an average voltage between segments not exceeding 20-30 volts.
- (4) In some machines, the pole shoes are made with slots in which an additional winding is placed, fig. 5.10. The currents in these "pole-face wdg's" or "compensating wdg's" are arranged to flow in directions opposite to those of armature conductors, so that their mmf's cancel out under the pole-face as shown in fig. 5.10. Compensating wdg's are connected in series with the armature, fig. 5.11, so that cancellation occurs for all loads (as I_A increases, AR will increase, but so will the compensating wdg mmf also). For full compensation, we must have

$$(\frac{1}{2}N_c)I_A = \alpha(Z/8p_a)I_A \quad \Rightarrow \quad N_c = \alpha Z/4p_a = \alpha NC/2p_a$$

where N_c = CW conductors per pole, and α = pole arc/pole pitch. Computing N_c in this way, it is unlikely to come out an integer; a smaller integer number is used because 60-70 % compensation is usually sufficient. Compensating wdg's are very expensive to install; they are economically justified only in very large machines, and in some special-purpose machines.

5.5 Brush shift

Sometimes brushes are not in the exact neutral position (q-axis). Such brush shift may be (a) unintentional : incorrect positioning in manufacture, or poor brush fit, etc., or it may be (b) intentional : in very old machines and in some very small machines, brushes are shifted to improve commutation (see Chapter 6 for details). With the brushes thus shifted, the arm field is no longer in strict quadrature with the main field (i.e. d-axis), fig. 5.12. The d-axis component of the arm field may oppose (demagnetizing) or aid (magnetizing) the main field; this depends on the direction of brush shift relative to rotation, and on the mode of operation, generating or motoring; see fig. 5.12.

To test for correct positioning of brushes, the machine is rotated in both directions as a loaded generator; if the load, speed, and field excitation are the same for both directions of rotation, the terminal voltage will be the same if the brushes are correctly placed. If, however, the brushes are not at the exact neutral position, the terminal voltage will differ for the two directions of rotation.

CHAPTER 6 : COMMUTATION

The commutator is a characteristic feature of dc machines. Its purpose is to match the alternating currents and voltages of the armature coils to the direct current and voltage of the brushes as already explained in chapters 1 and 3. However, the commutation process is quite complicated, and gives rise to secondary effects that place limits on the over-all performance of the machine. This chapter explains the commutation process and its main effects.

6.1 The process of commutation

Fig. 6.1 shows a general arm coil C moving to the right as it rotates with the armature; it is connected to commutator bars a and b which move with it. (a) When the coil sides are under the poles, the coil is part of a certain armature path and carries a path current I_a

$$I_a = I_A / 2a$$

(b) As the coil sides approach the q-axis (or brush axis), there will be an instant t_1 at which the brush contacts bars a and b simultaneously; thus starts the short circuit of the coil by the brush.

(c) The coil continues to be short-circuited by the brush; it is said to be 'undergoing commutation'. (d) As coil sides move away from the q-axis, there will be an instant t_2 at which bar b breaks contact with the brush so that the short circuit ends. (e) Coil sides move under poles, and the coil is now part of a different path; the coil current is I_a again, but in a direction opposite to the original one.

Clearly, then, the coil is short-circuited for an interval T_c

$$T_c = t_2 - t_1$$

During this interval, the coil current changes from I_a to $-I_a$; i.e. it reverses or 'commutates'. As shown in Fig. 6.2, the change in current must follow some time-curve from the point (t_1, I_a) to the point $(t_2, -I_a)$. Depending on various conditions that will be explained in later sections, we may have linear commutation (curve 1), over-commutation (curve 2), or under-commutation (curve 3).

To calculate the SC interval (or commutation interval), let u_c denote the speed of the bars; thus

$$u_c = 2\pi r_c n$$

where r_c is the radius at the commutator surface. From fig. 6.3, it is seen that the leading edge of bar a moves from x_1 at t_1 to x_2 at t_2 ;

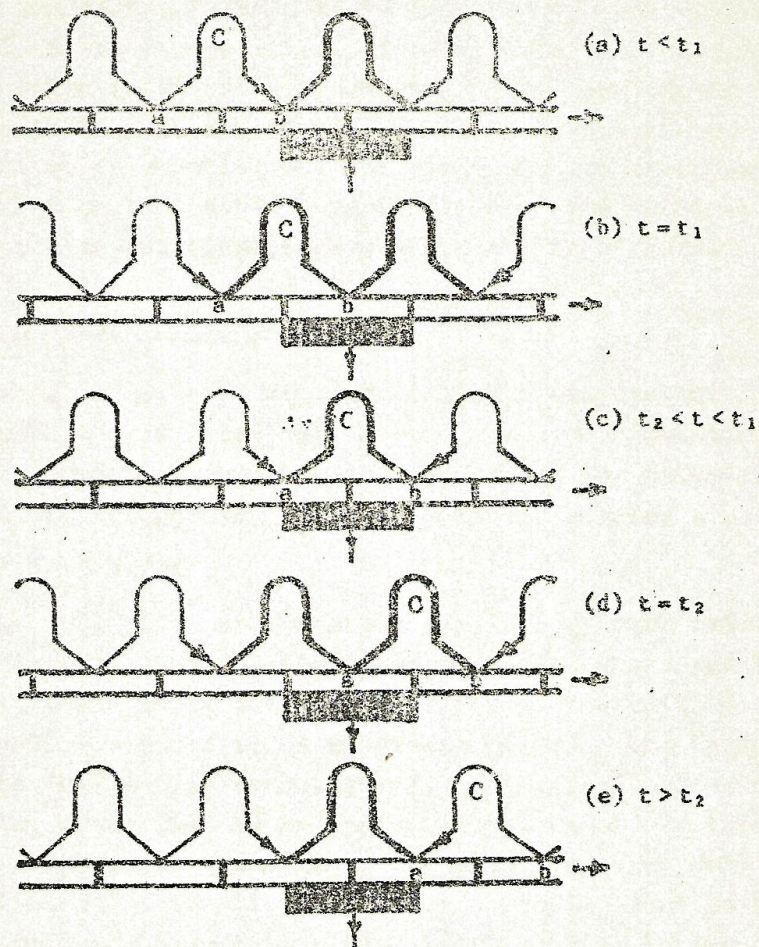


Fig. 6.1 The process of commutation.

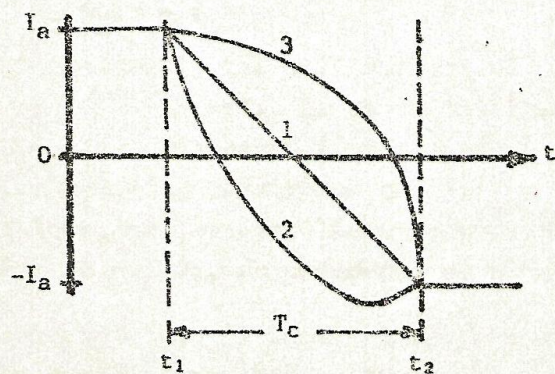


Fig. 6.2 Reversal of current in coil undergoing commutation.

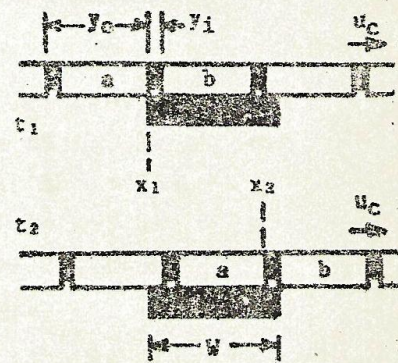


Fig. 6.3

Aid to the calculation of commutation time T_c .

thus

6.3

$$u_c = \frac{x_2 - x_1}{t_2 - t_1} = \frac{W - y_1}{T_c}$$

Therefore

$$T_c = \frac{W - y_1}{u_c} = \frac{1}{2\pi r_c n} \left(\frac{W}{y_o} - \frac{y_1}{y_o} \right) y_o = \frac{1}{nC} \left(\frac{W}{y_o} - \frac{y_1}{y_o} \right) \quad (y_o = \frac{2\pi r_c}{C})$$

As expected, the length of the SC interval, T_c , is determined by the speed of rotation n , the relative dimensions of bars and brush, and the number of commutator bars.

6.2 Equivalent circuit of commutating coil

During commutation, the coil SC current i_s circulates in a path composed of : the coil itself, risers, bars, contact surfaces, and brush (see fig. 6.4). A simplified equivalent circuit is shown in fig. 6.5 with :

- R_c = coil resistance;
- e_c = rotational emf in coil = $2N(b\omega)$;
- L_c = self inductance of coil;
- r_1 = contact resistance between brush and trailing bar;
- r_2 = contact resistance between brush and leading bar.

The circuit of fig. 6.5 involves the following simplifications :

- the resistance of riser, bar, and brush is negligible wrt contact resistance;
- mutual inductance with adjacent coils is neglected;
- brush assumed to short circuit one coil at a time.

Note that lower-case symbols are used for quantities that are time-varying during T_c ; these are e_c , i_s , i_1 , i_2 , r_1 , and r_2 ; indeed, i_s and possibly e_c reverse during T_c . Also note that from KCL

$$i_1 = I_a - i_s \quad \text{and} \quad i_2 = I_a + i_s$$

so that

$$i_1 + i_2 = (I_a - i_s) + (I_a + i_s) = 2I_a$$

as expected.

The terminal voltage of the coil v_c is given by

$$v_c = e_c - i_s R_c - L_c (di_s/dt)$$

The rotational emf e_c is small because field is small around the q-axis (see, for example, fig. 5.5). $L_c (di_s/dt)$ is called the reactance voltage; it is induced by the change in i_c .

is

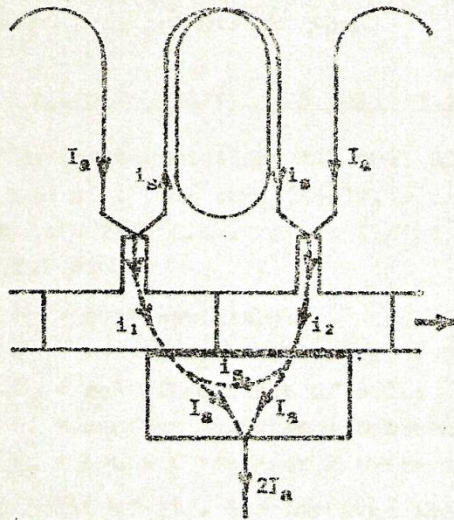


Fig. 6.4 Current distribution in brush and commutating coil.

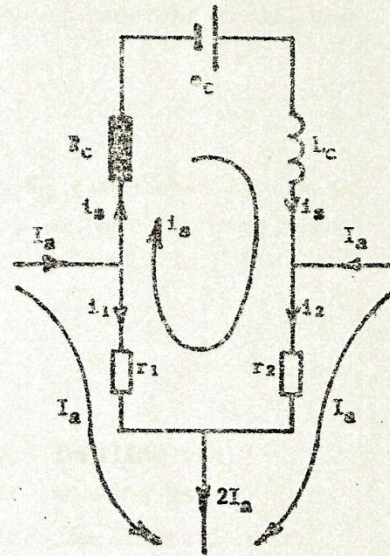


Fig. 6.5 Equivalent circuit for brush and commutating coil.

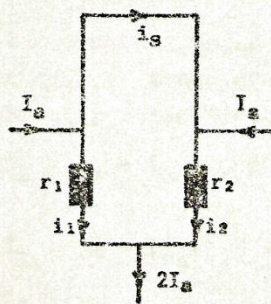


Fig. 6.6 Simplified equivalent circuit for resistance commutation.

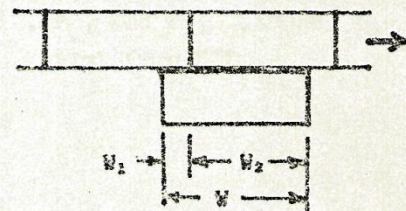


Fig. 6.7 Brush contact areas :
 $A_1 = W_1 l_b$, $A_2 = W_2 l_b$, $A_b = W l_b$;
 l_b = axial length of brush.

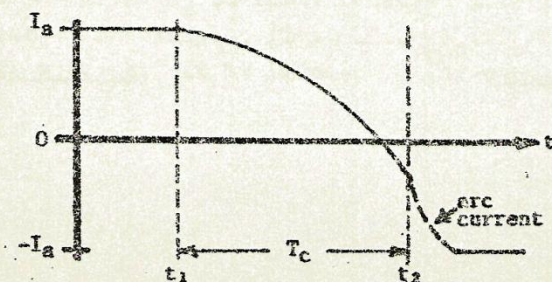


Fig. 6.8 Sparking caused by under-commutation due to reactance voltage.

6.5

6.3 Linear commutation (resistance commutation)

In small machines, the coil voltage v_c is smaller than the contact drops $i_1 r_1$ and $i_2 r_2$. If we assume that v_c is negligibly small, then the equivalent circuit of fig. 6.5 reduces to that of fig. 6.6. In this case, r_1 and r_2 are in parallel so that by current division

$$\frac{i_1}{i_2} = \frac{r_2}{r_1}$$

If we further assume that r_1 and r_2 are linear resistances (which in fact they are not), then

$$\frac{r_1}{r_2} = \frac{A_2}{A_1}$$

where the contact areas A_1 and A_2 are defined in fig. 6.7. Thus

$$\frac{i_1}{i_2} = \frac{A_1}{A_2}$$

i.e. the current division between bars is in direct proportion to their respective contact areas. If in the above expression we substitute for i_1 and i_2 in terms of I_a and i_s (see section 6.2), and rearrange, we get

$$i_s = \frac{A_2 - A_1}{A_b} \cdot I_a \quad \text{(derive this equation)}$$

As the commutator slides against the brush at constant speed, A_1 increases linearly with time, while A_2 decreases linearly with time. Thus i_s varies linearly from I_a at t_1 to $-I_a$ at t_2 , and we have linear commutation as in curve 1 of fig. 6.2. Linear commutation is also called resistance commutation because the current variation is controlled by the contact resistances r_1 and r_2 (see first equation in this section).

Note that we derived linear commutation as an approximation based on two assumptions : negligible v_c and linear contact resistances. These assumptions do not generally hold in practice so that we seldom have linear commutation. Commutation approaches linearity in small machines where these assumptions are approximately true.

6.4 Reactance voltage

Reactance voltage is the voltage induced in the coil due to the time variation of i_s ; it appears across L_c in the equivalent circuit of fig. 6.5, and is equal to $L_c(di_s/dt)$. Reactance voltage has a great effect on the commutation process, so that linear commutation (which is

effect on the commutation process, so that linear commutation (which is

6.6

based on neglecting reactance voltage) is unlikely to be achieved in practice. The role of reactance voltage in the commutation process may be described qualitatively as follows :

The reactance voltage is induced by the change of coil current from I_a to $-I_a$. According to Lenz's law, the reactance voltage will be induced in such a way as to oppose what is causing it, i.e. it opposes the change in current. Therefore the reactance voltage retards or delays the change in current.

Due to reactance voltage, then, the current tends to follow a curve above that of linear commutation, for example curve 3 in fig. 6.2; the greater the coil inductance L_c , the higher the curve.

If current reversal is not complete (i.e. current has not reached $-I_a$) when bar b breaks contact with the brush at t_2 , the curve will be as shown in fig. 6.8. This results in sparking which is explained as follows :

At t_2 the coil current attempts to jump to $-I_a$ almost instantaneously. This results in very high reactance voltage (why ?), which causes breakdown in the air. The arc provides a path between brush and bar b through which current flows to complete its reversal to $-I_a$.

Sparking is harmful because it causes heating and hence wear of both brush and commutator bars. It becomes more severe as load increases (as the armature current I_A increases, so does the path current I_a).

Treatment of sparking

In some small machines, the resistive contact drop is much greater than the reactance voltage so that sparking is limited by the effect of resistance commutation, i.e. commutation approaches the linear case.

In larger machines, some additional means must be found to limit sparking, i.e. to counter the effect of reactance voltage which is the prime cause of sparking as explained above. Modern machines use interpoles, while older machines (and some small machines) use brush shift; these two methods are explained in sections 6.5 and 6.6.

6.5 Interpoles (commutating poles, compoles)

Nearly all integral horsepower machines have interpoles. Interpoles are narrow poles with large air gap placed between main poles as in fig. 6.9. Their coils are connected in series with the armature so

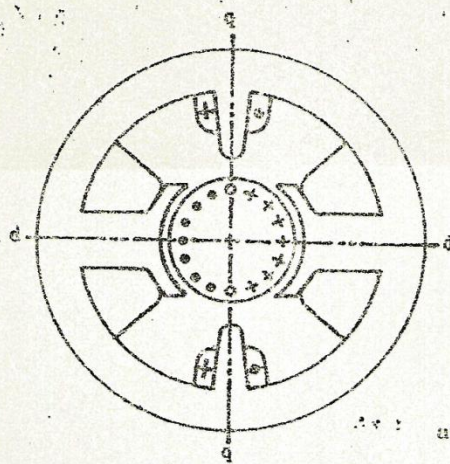


Fig. 6.9 Two-pole machine with interpoles.

Fig. 6.10

Flux density distributions in the air gap of a dc machine.

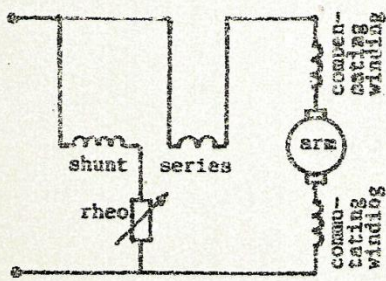
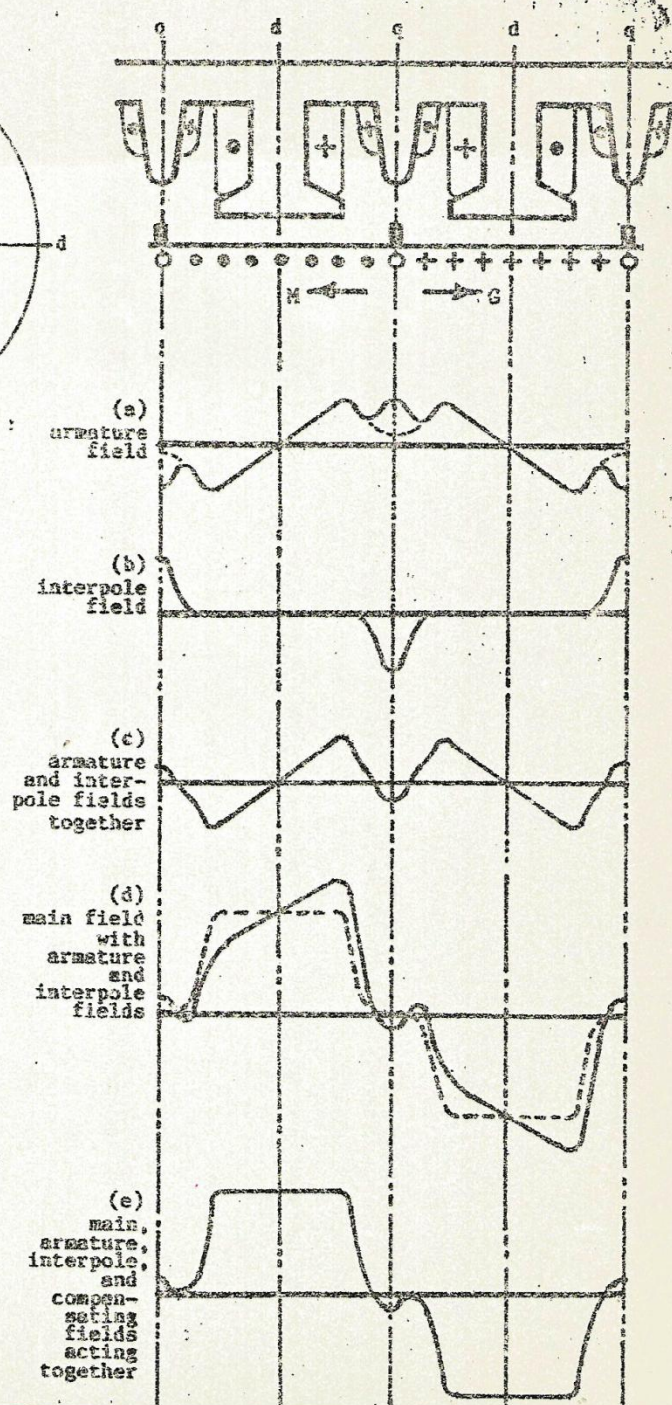


Fig. 6.11 Connection diagram of dc machine.



6.8

that the interpole field is proportional to armature current I_A (the large air gap prevents saturation in the iron). The interpole field acts on commutating coils at the q-axis.

The interpole mmf M_i is given by

$$M_i = N_i I_A$$

where N_i is the number of turns in each interpole coil. The number of turns N_i is chosen to make the interpole mmf some 25 % greater than M_{am} , the cross-magnetising armature mmf at the q-axis (see section 5.1); thus

$$M_i \approx 1.25 M_{am} \quad \text{so that} \quad N_i \approx 1.25 (NC/4pa)$$

In this way, M_i is made to serve two purposes : (1) it fully neutralises the armature reaction field, and (2) the additional 25 % neutralises the commutating coil flux (which induces the reactance voltage). This is clear in figs. 6.10 a, b, and c : the interpole field not only reduces the q-axis field to zero, but drives additional flux in the negative direction to neutralise reactance voltage. Figs. 6.10 d and e show the resultant field in interpole machines, without and with compensating windings; compare them with figs. 5.5 and 5.10. (NB interpoles treat arm reaction in the q-axis, while compensating wdgs treat arm reaction under the poles).

As the machine is loaded, the armature current I_A increases so that armature reaction and reactance voltage increase; but the interpole field is also proportional to I_A , and will increase automatically to neutralise armature reaction (in the q-axis) and reactance voltage. Interpoles will continue to do their job properly for either mode of operation, motor or generator, and for either direction of rotation, forward or reverse.

Fig. 6.11 shows the general connection of a dc machine. Not all windings shown are present in all machines. Interpole or commutating wdgs are found on integral horsepower machines (rated power greater than one hp); compensating wdgs are found on large machines and on some special machines; many machines have only one main field wdg, shunt or series; compound machines have both. The terminals of main field wdgs (shunt and series) are usually brought out to the terminal box to allow user manipulation; the terminals of compensating and commutating wdgs are not brought out to the terminal box so that they are permanently connected in series with the armature.

6.6 Brush shift

A second method for improving commutation to limit sparking is to shift the brushes from the q-axis. The principle is as follows :

Recall figs. 5.4 and 5.5 which show how the magnetic neutral axis ($mna : b = 0$) moves away from the q-axis due to armature reaction. If now the brushes are shifted in the same direction, they will be in a region where the armature field opposes the main field. At some location the two fields cancel out; placing the brushes at this location eliminates the rotational emf e_c (see fig. 6.5). This is not enough because there still is the reactance voltage. To neutralise reactance voltage, the brushes are shifted a little further in the same direction; the sides of commutating coil will then be subjected to a small (but nonzero) field that opposes the coil flux which induces the reactance voltage. If the opposing fluxes can be made equal, the reactance voltage is eliminated.

As a method for improving commutation, brush shift is not as good as interpoles because it has the following disadvantages :

1. As the load on the machine changes, the arm current I_A changes so that AR and the mna shift also change. For correct operation, the brush shift must be changed accordingly, which is impractical. In practice, the brushes are placed in a position that gives minimum sparking at rated load, so that there may be considerable sparking at other loads (eg no-load !).
2. From fig. 5.4, it is seen that the mna shifts in the direction of rotation for generator operation, and in the direction opposite to rotation for motor operation. Thus brush shift (which is in the same direction as the mna shift) cannot be used with motors intended to run in both directions, or with machines intended for variable mode of operation : if brush shift is correct for one case, it is incorrect for the other !
3. Brush shift causes demagnetising armature reaction (see fig. 5.12, left part).

Because of these disadvantages, brush shift is used only in small fractional horsepower machines (rated power less than one hp) where it is not economical to use interpoles. Brush shift was also used in old machines before the invention of interpoles.

CHAPTER 7 : POWER CONVERSION AND LOSSES

7.1

The input power to the dc machine undergoes electromechanical conversion to produce the output power; the process yields a number of losses that appear as heat which has harmful effects on the performance of the machine. In this chapter we study the conversion process and the losses associated with it.

7.1 Power balance

Most of the input power supplied to a dc machine is converted into useful output power; the remainder of the input power is lost as heat; see fig. 7.1. The principle of conservation of energy requires total power balance

$$P_{in} = P_{out} + \text{LOSSES}$$

It is sometimes useful to think of power as 'flowing' through the machine, fig. 7.2. Power flow is divided into two stages, the border line being the actual electromechanical energy conversion process.

P_c is the conversion power

$$P_c = E_A I_A = \omega_r T_d \quad (7.2)$$

E_A is the induced emf, T_d the developed torque, I_A the arm current, and ω_r the angular shaft speed. P_c is also called the internal power because it is defined within the machine; in contrast, P_{in} and P_{out} are external powers that can be measured. E_A and T_d in eqn 7.2 are internal quantities that cannot be measured directly. Power balance in fig. 7.2 requires that

$$P_{in} = P_c + \text{LOSS}_1 \quad \text{and} \quad P_c = P_{out} + \text{LOSS}_2 \quad (7.3)$$

The total loss is made up of 2 parts : LOSS_1 occurs before conversion, and LOSS_2 occurs after conversion. Clearly

$$P_{in} > P_c > P_{out} \quad (7.4)$$

Motor operation

The input power is electrical, and the output power is mechanical, fig. 7.3. Part of the input power is lost as electrical (copper) losses in the windings, and the remainder is available for electromechanical energy conversion; part of the converted power P_c is lost in supplying the losses due to rotation, and the remainder is available as a mechanical output power to drive the load. Note that

$$P_{mech} < P_c \Rightarrow \omega_r T_L < \omega_r T_d \Rightarrow T_L < T_d \quad (7.5)$$

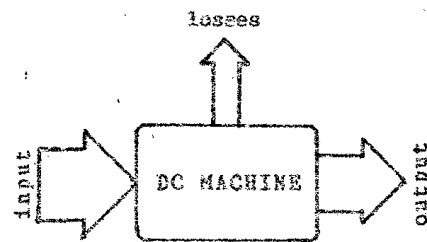


Fig. 7.1 Division of power in a dc machine.

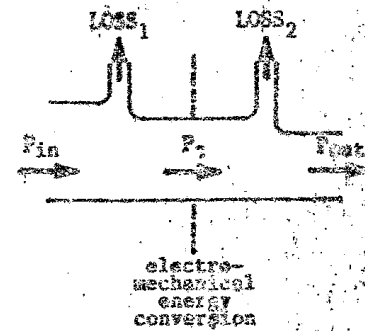


Fig. 7.2 Flow of power through a dc machine.

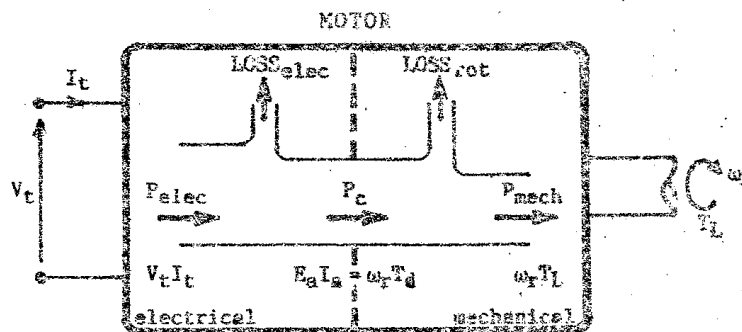


Fig. 7.3 Flow of power through a dc motor.

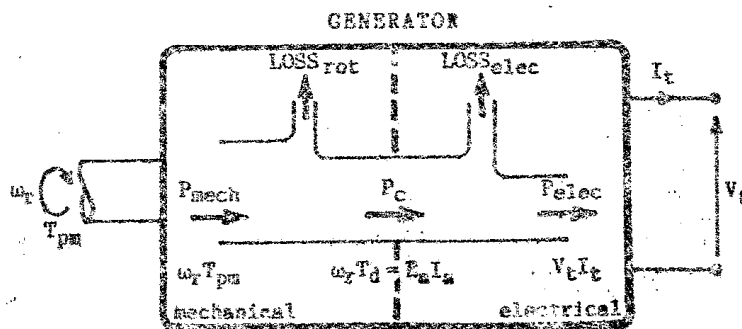


Fig. 7.4 Flow of power through a dc generator.

Fig.7.4 Flow of power through a dc generator.

7.3

That is, the shaft torque available at the load, T_L , is less than the developed torque T_d ; the difference is needed to overcome opposing torques within the motor (such as bearing friction)

Generator operation

The input power is mechanical, and the output power is electrical, fig. 7.4. Part of the input power is lost as rotational losses, and the remainder is available for electromechanical energy conversion; part of the converted power P_c is lost as electrical (copper) losses in the windings, and the remainder is available as electrical output power to supply the load. Note that

$$P_{\text{mech}} > P_c \Rightarrow \omega_r T_{\text{pm}} > \omega_r T_d \Rightarrow T_{\text{pm}} > T_d \quad (7.6)$$

That is, the shaft torque produced by the prime mover, T_{pm} , is greater than the developed torque T_d ; the difference is the torque needed to overcome friction and other opposing torques (other than T_d).

Remark

It is good practice to keep power balance always in mind : every power we define must come from somewhere and, conversely, every bit of it must go somewhere. This is true not only in dc machines, but in all physical systems; it often helps us in understanding the processes we study.

7.2 Losses

The losses of a dc machine are of various types and occur in different parts of the machine. Although different losses are produced differently, they all appear as heat, i.e. they represent conversion to useless thermal energy. The heat generated by the losses has two major effects :

- (i) Losses raise the temperature inside the machine, and thus affect the performance and life of the materials of the machine, particularly insulation. Therefore losses determine the upper limits on machine rating.
- (ii) Losses are a waste of energy, and energy costs money; therefore losses result in a waste of money (in the operating cost of the machine).

Losses cannot be eliminated, but they can be reduced by proper design; the design must also provide for ventilation to disperse the heat generated. Thus losses have a significant effect on the initial cost of the machine.

7.4

The cost of wasted energy in item (ii) above is important with industrial motors where the powers involved are quite high; it is not important with small control motors where the powers involved are very small. However, the temperature rise in item (i) is important for all motors.

Electrical losses

Electrical losses are also called copper losses, winding losses, I^2R losses, and ohmic losses. Copper losses occur in all windings (see fig. 6.11) due to the flow of current through them; they are

$$\text{LOSS}_{\text{arm}} = I_A^2 R_A = \text{armature circuit copper loss} \quad (7.7a)$$

$$\text{LOSS}_{\text{ser}} = I_c^2 R_c = \text{series field copper loss} \quad (7.7b)$$

$$\text{LOSS}_{\text{sh}} = I_f^2 R_f = \text{shunt field copper loss} \quad (7.7c)$$

In computing LOSS_{arm} , R_A includes the resistances of commutating and compensating windings (if present). The series field current I_s may or may not be equal to the armature current I_A , see fig. 4.2.

The copper loss in a given wdg is proportional to the square of the current in that wdg; if the current is doubled, the copper loss increases four times. LOSS_{arm} and LOSS_{ser} depend on armature current, and hence they depend on the load on the machine (I_A increases with load). LOSS_{sh} depends on the terminal voltage, and varies with its square.

The above expressions can be used to calculate copper losses using measured values of winding resistances. The wdg resistance must be at the correct wdg temperature; if the temperature at which the loss is required is not known, it is assumed to be 75 °C. If the wdg resistance is known (say by measurement) at a temperature T_1 , it can be found at a different temperature T_2 from

$$\frac{R_2}{R_1} = \frac{T_2 + 234.5}{T_1 + 234.5} \quad (7.8)$$

The brush contact loss is also an electrical loss. Since the brush contact drop V_b is approximately constant over a wide range of armature currents, the loss is proportional to the armature current itself (and not its square as in wdg losses) :

$$\text{LOSS}_{\text{contact}} = I_A V_b \quad (7.9)$$

7.5

Magnetic losses

Magnetic losses are also called iron losses or core losses. They result from hysteresis and eddy currents in cores subjected to varying magnetisation, i.e. mainly in the armature teeth and core, but also in the pole shoes (due to armature slotting - see fig. 4.2b).

Iron losses are distributed in the cores in complicated patterns, so that there are no simple formulae that give their values accurately. It is known, however, that iron losses depend on the magnetisation level (flux density) in the cores, and on the frequency with which it alternates, $f = np$. For the hysteresis loss, we have

$$\text{LOSS}_{\text{hyst}} \propto f B_{\text{max}}^x \quad (7.10)$$

where the constant of proportionality is determined by the volume of the core and its magnetic characteristics (hysteresis loop). The Steinmetz exponent x depends on the type of iron used, and ranges from 1.5 to 2.5 (usually around 2); it is an empirical constant (obtained from experience and testing, not from electromagnetic theory). For the eddy current loss, we have

$$\text{LOSS}_{\text{eddy}} \propto f^2 B_{\text{max}}^2 (\text{lamination thickness})^2 \quad (7.11)$$

where the constant of proportionality is determined by the volume of the core and its electrical characteristics (resistivity). Clearly, thin laminations reduce eddy current losses. The armature is always laminated, and the pole shoes are usually laminated. If a motor is to be driven from a modern solid-state controlled rectifier, all cores are laminated (including poles and yoke).

Mechanical losses

Mechanical losses arise from friction and windage (friction with air) during rotation. They depend on the speed of rotation, each type of mechanical loss being proportional to some power of n . Bearing friction loss depends on the type of bearing used and on the viscosity of the lubricant; improper lubrication (too little or too much) increases the loss. Brush friction loss is proportional to the area of contact and to the brush pressure; it also depends on the brush and commutator materials, their state of polish, and the temperature at the contact surface; it is often the largest friction loss. Windage losses arise from moving the air around the armature (air friction); they depend on the shape of the rotating surface (smooth or rough). Ventilation loss is an additional windage loss due to fans and vent

7.6

Stray load loss

Stray load losses are additional losses that occur in the machine when loaded, and cannot be included with the conventional losses listed above. They include :

- additional core loss resulting from armature reaction distortion;
- copper loss due to short circuit current during commutation (in commutating coils, commutator segments, and brushes);
- nonuniform current distribution in large armature conductors.

Stray load losses are small and difficult to calculate. They may be neglected for small machines, and are usually assumed 1 % of output for large machines.

7.3 Classification of losses

Table 7.1 is a brief summary of the losses described in section 7.2; it gives their types (electrical, magnetic, or mechanical) and the main factors they depend on. The table also classifies the losses according to whether or not they are 'rotational' losses, and according to whether they are constant or vary with load. We now explain these two classifications.

Rotational losses

Rotational losses are the losses arising from the rotation of the armature. They include friction and windage losses, as well as core losses (in dc machines, the power lost in the core is not supplied by the source of the field, but by the torque that rotates the armature - see figures 7.3 and 7.4):

$$LOSS_{rot} = LOSS_{core} + LOSS_{mech} \quad (7.12)$$

Rotational losses increase with speed; the various component losses are functions of different powers of speed. Rotational losses exist even when the machine is running at no load because they do not depend on the armature current; therefore they are sometimes called 'no load losses'.

Rotational losses are supplied by the difference between the external and developed torques :

$$\text{motor (fig. 7.3) : } LOSS_{rot} = P_c - P_{mech} = \omega_r (T_d - T_L) \quad (7.13)$$

$$\text{generator (fig. 7.4) : } LOSS_{rot} = P_{mech} - P_c = \omega_r (T_{pm} - T_d) \quad (7.14)$$

Table 7.1 Classification of losses in dc machines.

loss	type	rotational	with load	dependence
1 armature circuit copper loss	elec	x	variable	$\propto I_A^2$
2 series field copper loss	elec	x	variable	$\propto I_A^2$
3 shunt field copper loss	elec	x	constant	$\propto V_t^2$
4 brush contact loss	elec	x	variable	$\propto I_a$
5 hysteresis loss	mag	✓	constant	$\propto f B_{max}^x$
6 eddy current loss	mag	✓	constant	$\propto f^2 B_{max}^2$
7 friction loss	mech	✓	constant	$\propto \text{power}$
8 windage loss	mech	✓	constant	$\propto \text{power}$
9 stray load loss		✓	variable	

Table 7.2 Typical values of dc machine losses for industrial motors in the range 1-100 kW; lower percentage losses are for the higher rated motors.

losses	percent of rated power
armature circuit electrical loss	3-6 %
shunt field electrical loss	1-5 %
rotational losses	3-15 %

Table 7.3 Typical efficiencies of industrial motors.

rated power, kW	
1	75 %
50	90 %
500	94 %
5000	97 %

7.8

Constant and variable losses

Constant losses are losses that do not change as the load on the machine changes; they are independent of armature current, and include mechanical losses, core losses, and shunt field loss. Variable losses are losses that increase as the load on the machine increases; they are electrical losses including armature circuit copper loss, series field loss, and brush contact loss. Copper losses increase with I_A^2 , while brush contact loss increases with I_A itself. We may therefore write

$$\text{LOSSES}_{\text{total}} = K_0 + K_1 I_A + K_2 I_A^2 \quad (7.15)$$

The first term on the RHS represents constant losses, while the second and third terms represent variable losses. At full load, constant losses are 4-20 % and variable losses are 3-6 %; see table 7.2.

Remark

Stray load losses are indeterminate functions of armature current and speed. They complicate classification, but are small enough to be neglected in most cases.

7.4 Measurement of losses

There are a number of practical tests to measure the various machine losses. In most cases, a given test yields the sum of two or more losses together; sometimes the component losses can be separated by further testing.

In testing, it is quite easy to measure electrical quantities (resistance, voltage, and current) and speed, somewhat difficult to measure torque, and quite difficult to measure magnetic quantities (flux and flux density). Powers are determined, on the electrical side, by the product of voltage and current, and on the mechanical side by the product of torque and angular speed.

In a load test, the machine is loaded at a given speed and field excitation (i.e. field current); the input and output powers are measured. The total loss at that speed, excitation, and load is obtained from eqn. 7.1 :

$$\text{LOSSES}_{\text{total}} = P_{\text{in}} - P_{\text{out}} \quad (7.16)$$

The total loss can be separated into electrical and rotational losses by calculating $I^2 R$ products in the various windings using wdg currents measured during the load test and (hot) wdg resistances measured previously. With the electrical losses thus calculated, the

7.9

rotational losses are obtained from

$$\text{LOSS}_{\text{rot}} = \text{LOSSES}_{\text{total}} - \text{LOSS}_{\text{elec}} \quad (7.17)$$

Load tests for large machines are impractical in test labs : they require very large loads, and waste large amounts of energy. There are other tests that yield the losses individually.

In a no load test, the machine is driven by a suitable prime mover (possibly another machine - see fig. 7.5) with its terminals open circuited (i.e. it operates as an unloaded generator). The input power to the test machine is measured mechanically (torque and speed), or electrically by measuring the input power to the drive motor and subtracting its losses (which must therefore be known). If the test machine is unexcited then $P_{\text{in}} = \text{LOSS}_{\text{mech}}$. If the test machine is then excited but left unloaded we get $P_{\text{in}} = \text{LOSS}_{\text{rot}}$; the core loss is obtained from $\text{LOSS}_{\text{core}} = \text{LOSS}_{\text{rot}} - \text{LOSS}_{\text{mech}}$. (Exercise : suggest a test for separating the brush friction loss).

If no suitable drive (prime mover) is available, rotational losses may be obtained by running the machine as a motor with no external load; this is the running light test, or Swinburne test. The input power will mainly go to rotational losses, but there will also be a little copper loss (why ?) The copper loss may be computed and subtracted from the input power to yield rotational losses. In the running light test, rotational losses cannot be separated into mechanical and core losses (why ?).

As seen from the above tests, it is always possible to determine copper losses from the measured values of wdg currents during the tests, and previously measured wdg resistances. Winding resistances are measured by standard methods (voltmeter-ammeter, wheatstone bridge, etc.); the wdg temperatures must be monitored at the time of resistance measurement (why ?), or the measurement is made with the machine hot (for example directly after a load test).

The no load and running light tests determine machine losses without loading it. Other tests have been devised to operate the machine at full load conditions without requiring an external load. An example of such tests is the opposition test (Kapp-Hopkinson test) which requires two identical machines. The machines are coupled mechanically, and connected in parallel with each other to the mains, fig. 7.6. By increasing the excitation for one machine and decreasing it for the other, the first will operate as a generator, and the

7.10

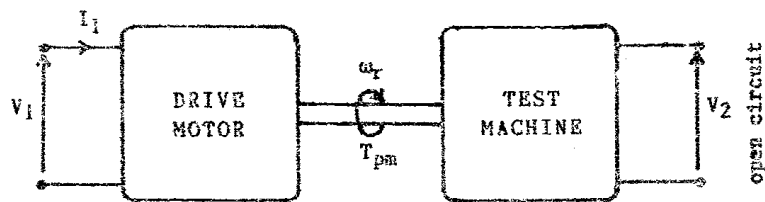
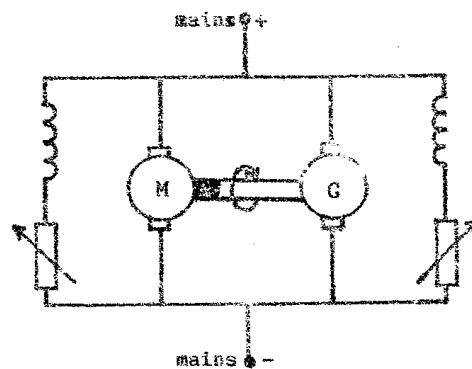
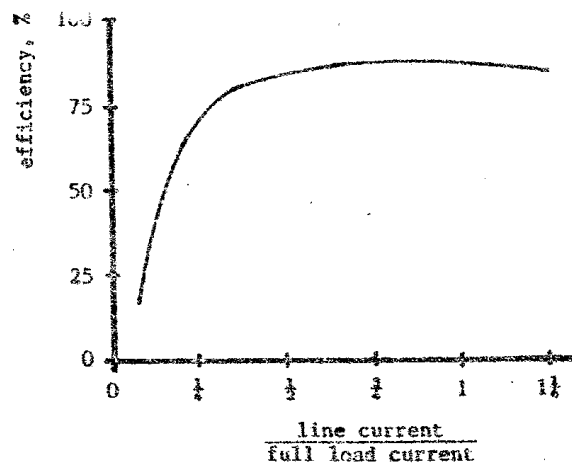


Fig. 7.5 No-load test on a dc machine.

Fig. 7.6
Opposition testFig. 7.7
Typical
efficiency curve
for a dc machine

7.11

second as a motor : the generator supplies the motor electrically, while the motor drives the generator mechanically; the power input from the mains supplies the losses to keep the system running. By suitable adjustments of the field rheostats, the armature currents can be set to their rated values. With the two machines running at or near rating (current, voltage, and speed), they will develop full load losses, yet the disadvantages of a load test have been avoided : no external load is needed, and the mains supplies only machine losses, not their full power.

In a heat run (or temperature-rise test), the machine is run at full load to develop full-load losses; the test takes 20-60 minutes until the temperature reaches steady state corresponding to its rated operating value. The no load and running light tests cannot replace the load test in a heat run because they do not generate all machine losses simultaneously. An opposition test, on the other hand, can be used in a heat run.

7.5 Efficiency

The efficiency of a machine is defined by

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + \text{LOSSES}} = 1 - \frac{\text{LOSSES}}{P_{in}} \quad (7.18)$$

The first expression is general, the second is suitable for generators (P_{out} measured electrically), and the third is suitable for motors (P_{in} measured electrically). The efficiency is a fraction less than unity, and is usually expressed in percent. Table 7.3 lists typical values of dc machine efficiencies.

The general definition of efficiency given above can be analysed into two component efficiencies corresponding to the two stages of power flow in fig. 7.2 :

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_c}{P_{in}} \frac{P_{out}}{P_c} \quad (7.19)$$

For a motor, fig. 7.3, this becomes

$$\eta = \frac{P_c}{P_{elec}} \frac{P_{mech}}{P_c} = (\text{eff of conversion})(\text{mech eff}) \quad (7.20)$$

and for a generator, fig. 7.4, it becomes

$$\eta = \frac{P_c}{P_{mech}} \frac{P_{elec}}{P_c} = (\text{eff of conversion})(\text{elec eff}) \quad (7.21)$$

7.12

Maximum efficiency

In section 7.4 we divided losses into constant and variable (see table 7.1); the efficiency was then expressed as in eqn. 7.15. Now consider motor operation : neglecting the small shunt field current, the input power is written

$$P_{in} = V_t I_A \quad (7.22)$$

Using the third expression in eqn. 7.15, the efficiency is written

$$\eta = 1 - \frac{K_0 + K_1 I_A + K_2 I_A^2}{V_t I_A} = 1 - \frac{1}{V_t} (K_0 I_A^{-1} + K_1 + K_2 I_A) \quad (7.23)$$

This gives efficiency as a function of armature current I_A ; the general shape of the resulting curve is shown in fig. 7.7 (where line current is approximately equal to arm current).

To locate the point of maximum efficiency, we differentiate eqn. 7.23

$$\frac{d\eta}{dI_A} = -\frac{1}{V_t} (-K_0 I_A^{-2} + K_2) \quad (7.24)$$

and equate to zero

$$\frac{d\eta}{dI_A} = 0 \Rightarrow K_0 = K_2 I_A^2 \quad (7.25)$$

Thus maximum efficiency occurs when the copper losses $K_2 I_A^2$ equal the constant losses K_0 (or, as an approximation, when variable losses equal constant losses - i.e. assuming the brush contact loss $K_1 I_A$ is small). Industrial machines are usually designed to have maximum efficiency for I_A between half and full load values (because the machine operates at less than full load most of the time); the exact choice is not critical because the efficiency curve is flat around the maximum value, fig. 7.7.

Importance of efficiency

For industrial motors, traction motors, and other power-application motors, efficiency is quite important, but it is only one of a number of factors that determine how good a machine is; the other factors include power/weight ratio, power/cost ratio, reliability, maintenance requirements, vibration and noise, etc. For small control motors, efficiency is of little importance; the main factors of interest include accuracy, cost, size, speed of response, reliability, noise, weight, interference, etc.

CHAPTER 8 : GENERATOR OPERATION

In generator operation, a dc machine is driven by a prime mover and supplies an electrical load. This chapter explains the operating characteristics of dc generators and the factors that affect them.

8.1 The voltage equation

In generator operation, we are interested in the voltage supplied at the output terminals. From KVL and the information of the previous chapters, the terminal voltage of a dc generator can be written

$$V = E_A - (\Sigma IR + V_b) \quad (8.1a)$$

$$= k_e n \phi_r - (\Sigma IR + V_b) \quad (8.1b)$$

$$= E_{Aoc} - (\Sigma IR + V_b + \Delta E) \quad (8.1c)$$

$$= k_e n \phi_m - (\Sigma IR + V_b + \Delta E) \quad (8.1d)$$

where $E_A = k_e n \phi_r$ is the induced emf in the armature, and ϕ_r is the actual (i.e. resultant) flux per pole; $E_{Aoc} = k_e n \phi_m$ is the induced emf on open circuit (no armature current), and ϕ_m is the flux per pole due to the main field. ϕ_r may be somewhat less than ϕ_m due to the demagnetising effect of armature reaction (chapter 5); ΔE represents the corresponding reduction in induced emf ($\Delta E = E_{Aoc} - E_A$, section 5.3). The difference between the induced emf E_A and the terminal voltage V is the sum of series resistive drops ΣIR (in the armature, series field wdg, commutating wdg, and compensating wdg) and the brush contact drop V_b . Eqn 8.1d tells us that the terminal voltage is determined primarily by the speed n and the main field flux ϕ_m , with some reduction due to series voltage drops and armature reaction.

Speed of rotation

The speed is set at the prime mover, not the generator itself. Of course the generator is a mechanical load on the prime mover, and hence affects its operation : as the electrical load on the generator increases, the armature current I_A increases thus increasing the developed torque $T_d (= k I_A \phi_r)$; if the prime mover torque does not increase to balance the increase in T_d , it will slow down (reducing E_A , hence V , hence I_A , hence T_d). However, in many applications, the prime mover is equipped with automatic control that maintains the speed almost constant (eg governor : as speed begins to fall, the governor enlarges the steam openings to the turbine).

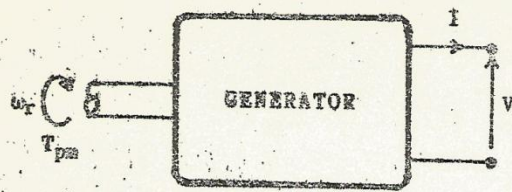


Fig. 8.1
Generator operation.

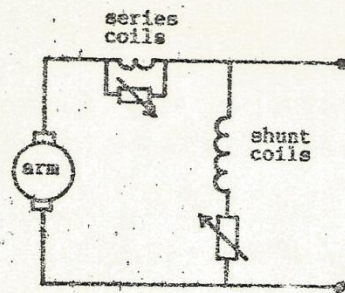


Fig. 8.2
DC machine with
field control
resistors.

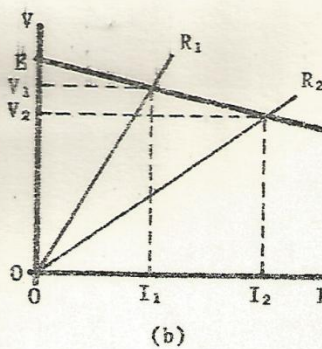
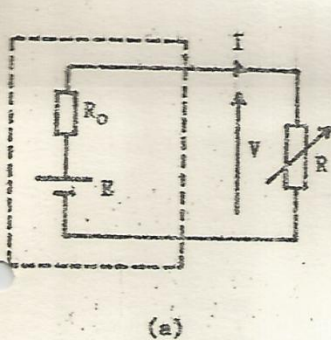


Fig. 8.3
Simple voltage
source :
(a) circuit
diagram;
(b) external
characteristic.

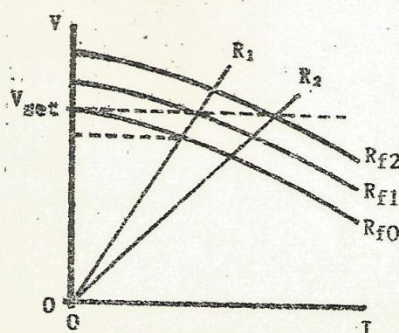


Fig. 8.4
Voltage control of
dc generator through
field resistance.

Field excitation

The main Flux ϕ_m is determined by the field mmf through the magnetisation curve, or we say that E_{Aoc} is determined by the field excitation current through the OCC; see section 4.3. The shunt field excitation may be controlled by means of variable resistance in series with the shunt field wdg, and the series field excitation may be controlled by means of a small variable resistor (diverter) in parallel with the series field wdg; see fig. 8.2.

Voltage drops

The series resistive drops ΣIR and the armature reaction drop ΔE increase with load (why ?); the brush contact drop V_b is practically constant over the normal working range of I_A . The total drop is generally small (small wdg resistances, and small demagnetising effect of armature reaction). For simplicity, we shall use the symbol ΔV for the total drop

$$\Delta V = \Sigma IR + V_b + \Delta E \quad (8.2)$$

so that eqns 8.1c and 8.1d become

$$V = E_{Aoc} - \Delta V \quad (8.3a)$$

$$= k_e n \phi_m - \Delta V \quad (8.3b)$$

8.2 Definitions

We shall need the terms and concepts defined below in our description of generator operation and the factors that affect it.

External characteristic

The external characteristic of a dc generator is the curve relating terminal voltage V and terminal current I (i.e. load current). The curve shows how voltage changes with load.

For a simple source circuit composed of constant emf E in series with constant internal resistance R_o , fig. 8.3a, the external characteristic is a straight line with negative slope, fig. 8.3b :

$$V = E - IR_o \quad (8.4)$$

Comparing eqn 8.4 with eqn 8.1d we see that the external characteristic of a dc generator will be different from that of fig. 8.3b not only because of the additional drops V_b and ΔE , but also because ϕ_m itself may change with load (if for example the generator has a series field).

8.4

We shall study the external characteristics of dc generators in sections 8.3 - 8.6 .

If a load resistance R_L is connected across the terminals of the simple source of fig. 8.3a, the terminal voltage and current will be

$$V_1 = \frac{ER_L}{R_0 + R_L} \quad \text{and} \quad I_1 = \frac{E}{R_0 + R_L} \quad (8.5)$$

The operating point (I_1, V_1) may also be found graphically by drawing the V-I characteristic of the load, and intersecting it with the external characteristic of the source, fig. 8.3b; the intersection is the point that satisfies both characteristics at the same time. For the typical drooping characteristic shown, it is seen that decreasing the load resistance increases the load current and decreases the terminal voltage ($R_2 < R_1$, $I_2 > I_1$, and $V_2 < V_1$).

Remark 1 : The graphical method can be used even when the external characteristic and the load V-I characteristic are nonlinear (not straight lines).

Remark 2 : The internal characteristic is the curve relating the emf and current. It is a horizontal line at E for the simple source of fig. 8.3a, but can be different in generators.

Voltage control

A given external characteristic corresponds to a fixed speed and fixed settings of the field control resistors. If the settings of the field resistors are changed, ϕ_m will also change (since the excitation currents are changed), and operation shifts to another curve. Therefore the operating point may be moved from one curve to another by changing the field excitation, fig. 8.4. The terminal voltage may be kept approximately constant by automatic regulators that sense the terminal voltage and increase or decrease the excitation to keep the voltage at the set value.

Voltage regulation

The voltage regulation of a generator at a given load is defined by

$$\text{voltage regulation} = \frac{\text{no load voltage} - \text{voltage under load}}{\text{voltage under load}} \quad (8.6)$$

It is a figure of merit that indicates how constant the terminal voltage is with load; a good voltage source should have small voltage regulation. The voltage regulation of generators equipped with automatic voltage control is almost zero.

8.5

8.3 Separately excited generator

If the field current of a separately excited generator is kept constant, Φ_m and E_{Aoc} will be constant. The external characteristic is then as shown in fig. 8.5 : V is less than E_{Aoc} due to the armature circuit resistive drop $I_A R_A$ (linear with current), the demagnetising effect of armature reaction ΔE (nonlinear function of I_A), and the brush contact drop V_b (constant - not shown in figure). The curvature of the characteristic comes from ΔE . Compare with the simple source of fig. 8.3.

8.4 Shunt generator

The external characteristic of the shunt generator, fig. 8.6, is similar to that of the separately excited generator, but has an additional drop due to shunt field weakening :

$$I_A \uparrow \Rightarrow \Delta V \uparrow \Rightarrow V \downarrow \Rightarrow I_f \downarrow \Rightarrow \Phi_m \downarrow \Rightarrow E_{Aoc} \downarrow$$

To explain this process in more detail, we first draw the OCC as in fig. 8.7; note that the OCC is obtained with the shunt field wdg disconnected from the armature and fed from a separate source. Next we draw the V - I characteristic for the shunt field resistance

$$V = R_f I_f \quad (8.7)$$

on the same graph. Now, for any field current I_f , the point (I_f, E_{Aoc}) must lie on the OCC, and the point (I_f, V) must lie on the R_f -line. At no-load the terminal current I is zero so that I_A is equal to I_f which is small, so that we may neglect the drop ΔV ; thus the terminal voltage V is equal to the induced emf E_{Aoc} . This condition is satisfied only at the point of intersection of the R_f -line with the OCC; therefore, at no-load, we have

$$I_f = I_{f0}, \quad E_{Aoc} = E_0, \quad V = V_0, \quad \text{with } V_0 = E_0 \quad (8.8)$$

Consider next the generator on load. I_A has increased so that the drop ΔV is now large enough to make V less than E_{Aoc} , eqn. 8.3a. Operation has to shift from the point of intersection : (I_f, E_{Aoc}) moves down the OCC, while (I_f, V) moves down the R_f -line. I_f will take up a position at which the difference between E_{Aoc} and V is equal to the drop ΔV :

$$I_f = I_{f1}, \quad E_{Aoc} = E_1, \quad V = V_1, \quad \text{with } V_1 = E_1 - \Delta V_1 \quad (8.9)$$

Comparing V_1 and $V_0 (= E_0)$, we see that the difference between them is the drop ΔV_1 plus an additional drop $(E_0 - E_1)$ due to the reduction of

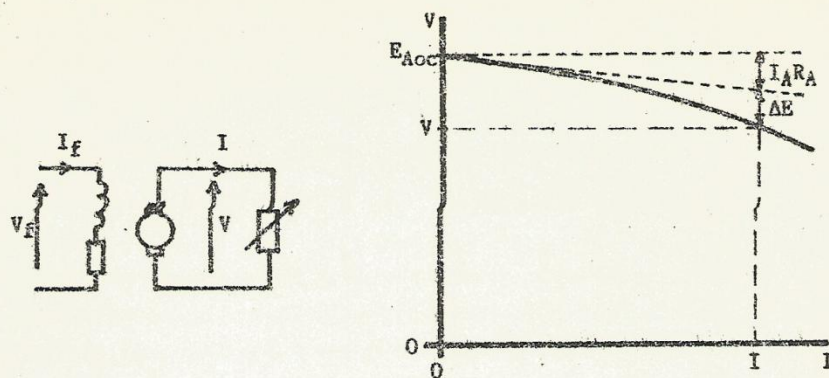


Fig. 8.5 Separately excited generator connection diagram and external characteristic (V_b not shown).

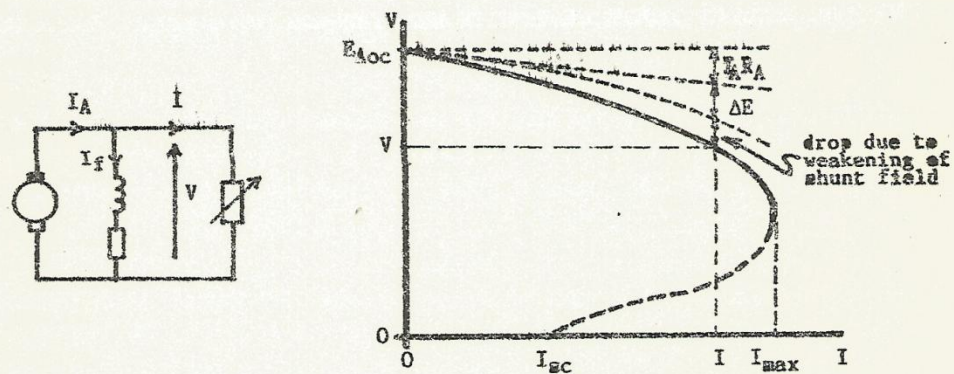


Fig. 8.6 Shunt generator connection diagram and external characteristic (V_b not shown).

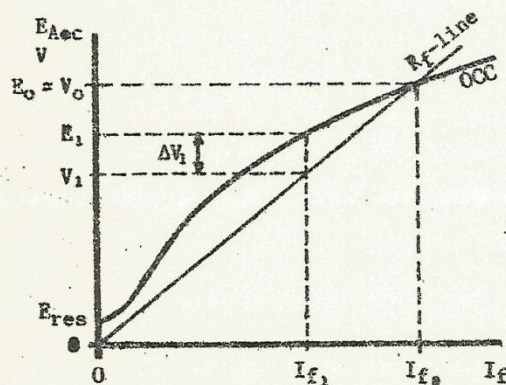


Fig. 8.7 Open circuit characteristic and field resistance line for shunt generator.

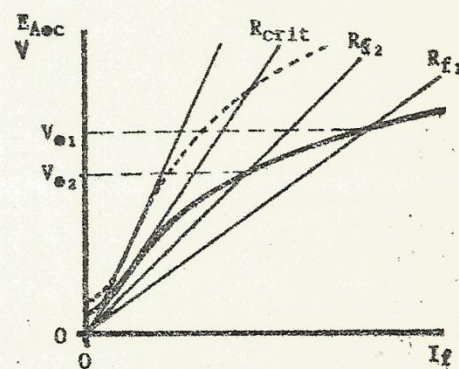


Fig. 8.8 Effect of field resistance on voltage build-up in shunt generator.

8.7

the induced emf E_{Aoc} from E_o to E_1 corresponding to the reduction of the field current I_f from I_{fo} to I_{f1} - as was stated at the beginning of this section.

At each value of load current I , the field current I_f moves to a position that makes the difference between the OCC and the R_f -line equal to the drop ΔV that corresponds to that load current or, more precisely, to the armature current I_A . If you study the OCC and the R_f -line carefully, you will see that there is a certain I_f at which the difference between them is maximum. Therefore there is a maximum armature current and hence a maximum load current, I_{max} in fig. 8.6; this is called the breakdown point.

The short circuit current of the shunt generator is inherently limited : at SC the terminal voltage V is zero so that $I_f = 0$; the emf is E_{res} (induced by the residual flux alone) which is very small. The resulting armature current is therefore small.

Voltage build-up

The preceding discussion helps us understand how the voltage of the shunt generator builds up. Assume that there is no load on the generator, and that there is an open switch in the field circuit so that $I_f = 0$, $E_{Aoc} = E_{res}$, and $I_A = 0$. If the switch is now closed, E_{res} is applied to R_f , and a small current I_f flows causing E_{Aoc} to climb up the OCC. But this increased value of E_{Aoc} is again applied to R_f and will increase I_f , which in turn increases E_{Aoc} some more. The process continues with (I_f, E_{Aoc}) climbing up the OCC and (I_f, V) climbing up the R_f -line until the two points coincide at the intersection point. We say that the shunt generator voltage V has 'built up' to V_o ; what stops the build-up process from continuing indefinitely is the curvature of the OCC, i.e. saturation.

(Exercise : how does KVL apply to the circuit during build-up ?)

The process of voltage build-up requires the following conditions to succeed :

- (1) There must be residual flux to start the process. A new generator, or one that has not been used for a long time, must be magnetised first. This is done by applying a separate dc source (for example a battery) to the field wdg for a short time; it is called 'flashing the field'.
- (2) The flux produced by I_f should aid the residual flux. If the field wdg is connected in the reverse direction, the voltage will 'build-down', i.e. it becomes less than E_{res} (i.e. almost zero).

8.8

- (3) The resistance of the field circuit R_f should be small enough to intersect the OCC in the saturation region. As R_f is made larger, the intersection moves down the OCC, fig. 8.8. The field resistance line that is tangent to the linear part of the OCC is called the critical field resistance, R_{crit} in fig. 8.8.: if R_f is increased further, there will be no build-up. The critical resistance is higher for higher speeds (why ?); the critical speed corresponding to a given field resistance is the speed at which the linear part of the OCC becomes tangent to that resistance. If the shunt generator fails to build-up at a certain speed due to large field resistance, it might build-up at a higher speed.

8.5 Compound generator

A compound generator is essentially a shunt generator with additional mmf from the series wdg :

$$\text{MMF}_{\text{total}} = N_f I_f \pm N_s I_s \quad (8.10)$$

The compounding is cumulative if the series field aids the shunt field (plus sign in eqn 8.10); the compounding is differential if the series field opposes the shunt field (minus sign in eqn 8.10). For long shunt connection, fig. 4.3, $I_s = I_A$, and for short shunt connection $I_s = I_A - I_f \approx I_A$. If a diverter is used, fig. 8.2, I_s may be less than these values.

The OCC of a compound machine corresponds to separate excitation of shunt field alone. Dividing eqn 8.10 by the shunt field turns

$$\frac{\text{MMF}_{\text{total}}}{N_f} = I_f \pm \frac{N_s}{N_f} I_s = I_{eq} \quad (8.11)$$

The term $(N_s/N_f)I_s$ is the series field excitation referred to the shunt field circuit; I_{eq} represents total excitation in terms of shunt field amperes, and can be read off p or projected directly on the horizontal axis of the OCC.

Cumulative compounding

As seen in section 8.4, the terminal voltage of a shunt generator drops due to ΔV and the reduction in E_{AOC} . In a cumulative compound generator, the series field compensates for part or all of the drop. The series field current changes with load (why ?) so that the degree of compensation changes with load. The number of series turns N_s may be chosen such that the resulting series field compensates exactly for

8.9

the drop at full load; the full load voltage is then equal to the no-load voltage (zero voltage regulation), and the machine is said to be flat-compounded (or level-compounded) - see fig. 8.9. If fewer series turns are used, we have under-compounding : the full load voltage is less than the no-load voltage (positive regulation), but still more than the shunt generator full load voltage. If more series turns are used, we have over-compounding : the full load voltage is greater than the no load voltage (negative regulation). It is also possible to choose N_s for over-compounding, and change the actual degree of compounding by means of a diverter, fig. 8.2.

Differential compounding

When the series field opposes the shunt field, it effectively increases the drops. The external characteristic is then below that of the shunt generator, fig. 8.9.

8.6 Series generator

The OCC for a series generator, fig. 8.10, is obtained with the field supplied from a separate source (the armature is open circuited by definition). In normal operation, the field wdg is connected in series with the armature, and the terminal voltage V is less than the induced emf E_{AOC} due to the drop ΔV ; the external characteristic is thus below the OCC as shown in fig. 8.10. The rising part of the curve is not stable : a slight change of load resistance causes large changes in terminal voltage and current. In the saturation region, the OCC is almost horizontal, but ΔV continues to increase with I_A so that the curve is falling; the fall is sharp in series generators designed to have strong demagnetising armature reaction.

8.7 Applications

For dc power generation, the separately excited generator has acceptable voltage regulation, but has the disadvantage of requiring a separate source. The self-excited shunt generator does not require a separate source, but has poor regulation. The cumulative compound generator overcomes this problem; it can be designed to have zero regulation by suitable compounding. Modern generators are equipped with automatic voltage control, possibly solid-state, so that they have excellent regulation; the design of the control system is determined by the external characteristic of the generator. However, solid-state rectifiers are rapidly replacing dc generators

8.10

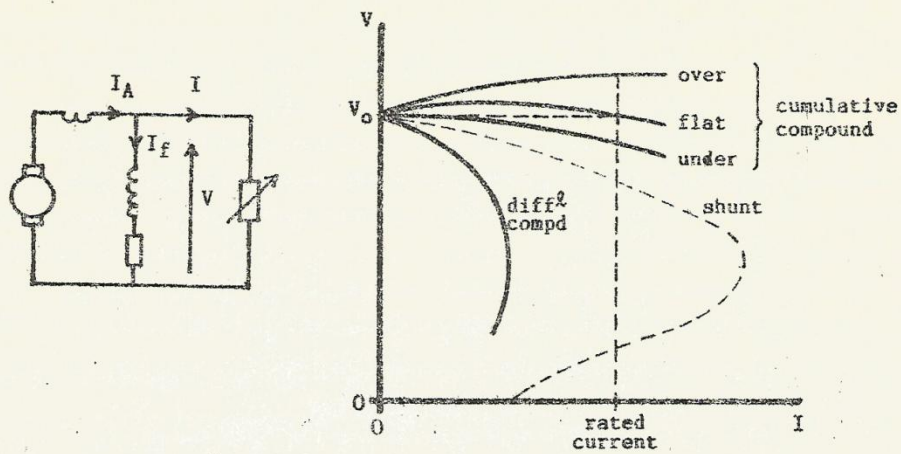


Fig. 8.9 Compound generator connection diagram and external characteristics for different cases.

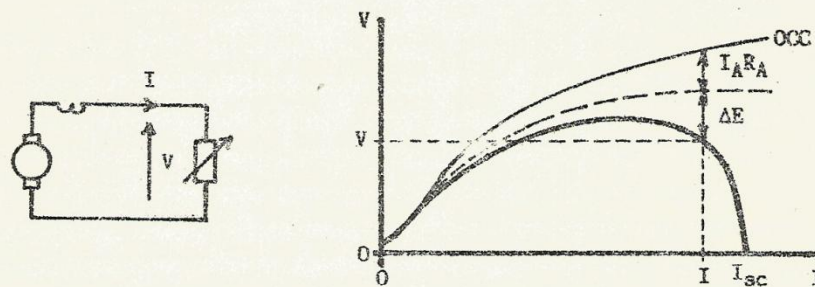


Fig. 8.10 Series generator connection diagram and external characteristic.

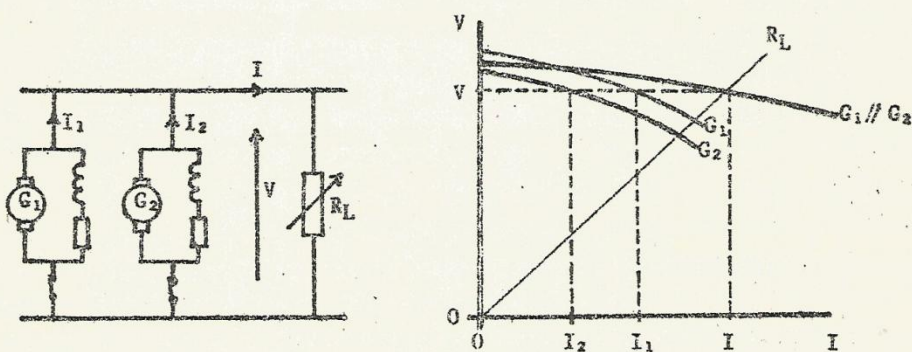


Fig. 8.11 Parallel operation of shunt generators.

8.11

in most applications; technological advances have made it possible to manufacture commercial solid-state components of high rating, i.e. components capable of passing high currents and withstanding high voltages. For example, the dc generator in the automobile has now been replaced by an ac generator (alternator) with rectifier.

The external characteristics of the series and differential compound generators make them unsuitable for dc power generation at constant voltage. The falling portions of their characteristics correspond to constant current operation over that range. The series generator has been used as a booster : it is connected in series with the line between a generator and its load; its rising characteristic compensates for the drop in the line.

8.8 Parallel operation

Two dc generators, or a generator and a battery, may be operated in parallel to supply a common load. The over-all characteristic is obtained by graphical parallel addition of their external characteristics, fig. 8.11. The figure also shows how the two generators share the load current according to their individual characteristics.

When we intend to operate two generators in parallel, before closing the paralleling switch we must make sure that the voltages of the two generators are equal and have the same polarity; otherwise large currents may circulate between them.

8.12

EXERCISE

The table represents the OCC of a dc machine at 850 rpm. The machine has a shunt field wdg of 600 turns and $20\ \Omega$. The armature circuit resistance is $0.25\ \Omega$.

NB Unless otherwise stated, you may neglect the demagnetising effect of armature reaction and the brush contact drop.

1. Separate excitation

The field wdg is connected in series with a variable resistor to a 330 V separate source.

- | I_f
A | E_A
V |
|------------|------------|
| 0. | 20 |
| 0.5 | 24 |
| 1 | 40 |
| 2 | 80 |
| 3 | 119 |
| 4 | 150 |
| 5 | 174 |
| 6 | 193 |
| 7 | 209 |
| 8 | 222 |
| 9 | 233 |
| 10 | 241 |
| 11 | 243 |
| 12 | 253 |
| 13 | 258 |
| 14 | 262 |
| 16 | 268 |
| 18 | 272 |
| 20 | 275 |
- 1.1 The field control resistor (FCR) is set to $10\ \Omega$. Plot the external characteristic up to a load current of 300 A. Find the load current and voltage regulation when the terminal voltage is 220 V. (112 A, 12.7 %)
- 1.2 Repeat 1.1 (on the same sheet) for a FCR of $20\ \Omega$. (20 A, 2.3 %)
- 1.3 Find FCR to make the terminal voltage 220 V at a load current of 180 A. ($2.3\ \Omega$)
- 1.4 Find the maximum possible load current at a terminal voltage of 220 V. (196 A)
- 1.5 Find the terminal voltage when the speed is changed to 1100 rpm, FCR is set to $10\ \Omega$, and the load current is 200 A. (271 V)
2. Shunt
- 2.1 For a speed of 850 rpm :
- What is the no-load voltage when FCR is shorted out ? set to $10\ \Omega$? set to $30\ \Omega$?
 - Find the critical resistance and short circuit current.
 - What is the critical speed when FCR is set to $10\ \Omega$? $30\ \Omega$?
 - What is the minimum speed at which the generator can build up ? (257.5 V, 208 V, 24 V; $40\ \Omega$, 80 A; 637.5 rpm, 1020 rpm; 425 rpm)
- 2.2 For a speed of 1100 rpm :
- Find the critical resistance and short circuit current.
 - Find the no-load voltage when FCR is shorted out. ($51.76\ \Omega$, 103.5 A; 345.5 V)
- 2.3 At 850 rpm and FCR shorted out :
- Plot the external characteristic.
 - Find the load current and VR when the terminal voltage is 220 V.

8.13

- 2.3 Find the terminal voltage, load current, and VR when the load resistance is 1.5Ω .
 2.4 What is the breakdown current ?
 (101 A, 17 %; 207 V, 138 A, 24.4 %; 291 A)
- 2.4 Estimate the value of FCR needed to make the terminal voltage 220 V at a load current of 80 A when the speed is 850 rpm. (4Ω)
- 2.5 The speed is 850 rpm and FCR is shorted out. V_b is 2 V, and armature reaction demagnetisation is not negligible. Find ΔE and ΔI_f when the terminal voltage is 220 V at a load current of 56 A. (12 V, 1.6 A)

3. Compound

The machine is connected in short shunt for cumulative compounding. The speed is 850 rpm.

- 3.1 With FCR shorted out, it is required to make the terminal voltage 220 V when the load current is 150 A. How many series turns are needed ? what is the voltage regulation ? Assume negligible series field resistance. (10 turns, 17 %)
- 3.2 The series field wdg has 15 turns and a resistance of 0.05Ω ; FCR is shorted out. V_b is 2 V and the demagnetising effect of armature reaction is not negligible. The terminal voltage is 220 V and the load current is 80 A. Find the armature current, the induced emf, and ΔE . (91.2 A, 259 V, 10.2 V)
- 3.3 The series wdg has 16 turns and a resistance of 0.05Ω ; FCR is set at some unknown value. The brush contact drop is 2 V, and the demagnetising effect of armature reaction is negligible. The load current is found to be 150 A when the shunt field current is 10 A. Find the terminal voltage, the value of FCR, and VR. (212.5 V, 2Ω , 17.6 %)

CHAPTER 9 : MOTOR OPERATION

In motor operation, a dc machine is supplied electrically, and drives a mechanical load, fig. 9.1; compare with fig. 8.1 for the dc generator. This chapter explains the operating characteristics of dc motors and the factors that affect them.

9.1 Governing equations

In motor operation, we are interested in the output torque and shaft speed, and their influence on the current drawn by the motor. From previous chapters, the emf and torque equations for a dc machine are

$$E_A = K_e n \phi \quad (9.1)$$

and

$$T_d = K_t I_A \phi \quad (9.2)$$

ϕ in these equations is the resultant useful flux per pole, i.e. it includes any demagnetisation due to armature reaction. E_A is the actual induced emf, and T_d is the developed torque. From KVL, we have

$$E_A = V - (\sum IR + V_b) \quad (9.3)$$

V is the voltage applied to the motor terminals, and $\sum IR$ is the total series resistive drop (armature wdg, commutating wdg, compensating wdg, series field wdg, and any additional series resistance). To simplify our study, we shall approximate this equation to

$$E_A = V - I_A R \quad (9.4)$$

i.e. the brush voltage drop is ignored, and R includes all resistances in the path of the armature current. Dividing eqn 9.4 by $K_e \phi$, and substituting from eqn 9.1, we get

$$n = \frac{V - I_A R}{K_e \phi} \quad (9.5)$$

This equation tells us that speed is determined primarily by the applied voltage V and the flux ϕ , with some reduction due to the series voltage drop $I_A R$ (which depends on current, and hence on load torque).

The above equations allow us to understand motor operation.

Load : torque and current

T_d in eqn 9.2 is the developed torque; it is slightly greater than the load torque T_L due to rotational losses (see chapter 7) :

$$T_d = T_L + T_{\text{rot loss}} \quad (9.6)$$

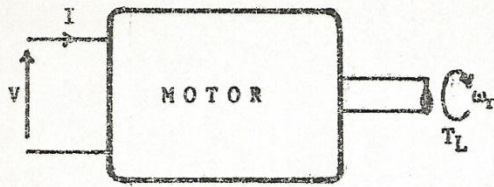
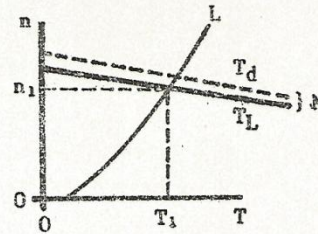
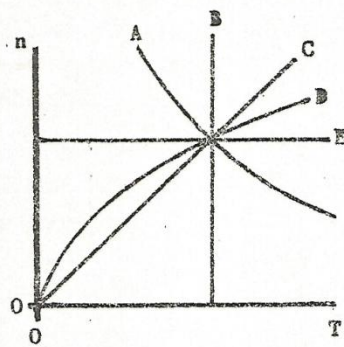


Fig. 9.1 Motor operation.

Fig. 9.2 Intersection of mechanical characteristics of motor M and load L to determine operating point (T_1, n_1) .

- A: $T \propto \frac{1}{n}$ (constant power; traction)
 B: $T = \text{constant}$ (traction; lifts; cranes)
 C: $T \propto n$ (machine tools)
 D: $T \propto n^2$ (fans; centrifugal pumps)
 E: $n = \text{constant}$ (ac alternators)

Fig. 9.3 Idealised torque/speed characteristics for typical mechanical loads.

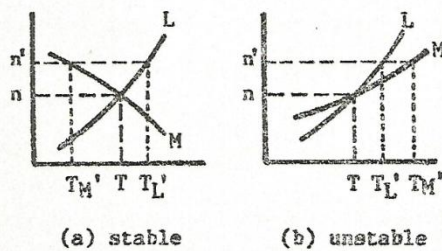


Fig. 9.4 Stability of operating point.

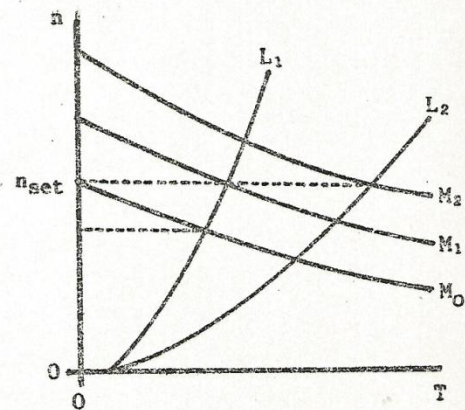


Fig. 9.5 Speed control of dc motor.

9.3

The greater the load on the motor, the greater the current it draws from the supply, eqn 9.2; that is, the load torque determines the current of the motor.

Actually, eqn 9.6 holds only under steady-state conditions, i.e. when the speed is constant. Under transient (or dynamic) conditions, the two sides of the equation are not equal, and the difference between them produces an acceleration

$$J \frac{d\omega_r}{dt} = T_d - (T_L + T_{\text{rot loss}}) \quad (9.7)$$

where J is the moment of inertia of the rotating parts (rotor, shaft, and load); $d\omega_r/dt$ is the angular acceleration. Eqn 9.7 is a development from Newton's law $F = ma$ (i.e. it relates to the mechanics of the system).

Suppose that the motor is running at some constant speed so that eqn 9.6 holds (i.e. $d\omega_r/dt = 0$ in eqn 9.7). Now suppose the load on the motor suddenly increases: the motor will slow down according to eqn 9.7. But this causes the induced emf to decrease, eqn 9.1. The resulting increase in the difference between V and E_A must be balanced by an increase in the armature current I_A , eqn 9.4. The increase in current increases the developed torque T_d , eqn 9.2, and the initial increase in load torque T_L is thus met. The motor now operates at steady state again, but at a reduced speed. The process is summarised as follows:

$$\begin{array}{ccccccc} T_L \uparrow & \Rightarrow & n \downarrow & \Rightarrow & E_A \downarrow & \Rightarrow & I_A \uparrow \Rightarrow T_d \uparrow \\ & & 9.7 & & 9.1 & & 9.4 & & 9.2 \end{array}$$

The reverse process is summarised by:

$$T_L \downarrow \Rightarrow n \uparrow \Rightarrow E_A \uparrow \Rightarrow I_A \downarrow \Rightarrow T_d \downarrow$$

Note that if the series resistance in eqn 9.4 is small, then only a slight change in speed is sufficient to cause large changes in armature current (and hence in developed torque).

After a disturbance (sudden change in load), the time it takes the motor to settle at a new speed is called the response time. It is determined by the electrical time constant of the motor and the mechanical time constants of the motor and connected load. In certain applications, particularly automatic control systems, the response must be quick, and the motor is designed to have low inductance and low inertia.

9.4

Applied voltage

The series resistance in the armature circuit is small, so that the induced emf E_A is approximately equal to the applied voltage V , eqn 9.4. Then, from eqn 9.1 we see that, for a given value of flux ϕ , the speed is determined primarily by the applied voltage V .

Field excitation

The flux ϕ is determined primarily by the main field mmf (i.e. by field current), and may be controlled by field resistors as in fig. 8.2. The torque is directly proportional to flux, eqn 9.2, but the speed is inversely proportional to it, eqn 9.5. Thus an increase in flux tends to decrease speed, and a decrease in flux tends to increase speed. Clearly, then, armature reaction tends to increase speed, while the series field in cumulative-compound motors tends to decrease speed.

9.2 Definitions

We shall need the terms and concepts defined below in our description of motor operation and the factors that affect it.

Mechanical characteristics

The mechanical characteristic of a dc motor is the curve relating the motor's two output variables, torque and speed; the curve shows how speed changes with load. Substituting for I_A from eqn 9.2 into eqn 9.5, we get

$$n = \frac{V}{K_e \phi} - \frac{R}{K_e K \phi^2} T_d \quad (9.8)$$

For constant V and ϕ , eqn 9.8 represents a straight line with negative slope, fig. 9.2. The first term on the RHS gives the vertical intercept (no-load speed), and the coefficient of T_d in the second term gives the slope. The load torque T_L is a little less than the developed torque T_d , eqn 9.6, so that the relationship curves below the straight line. The shape of the curve may be further modified due to changes in the flux ϕ (which affects both slope and intercept) as the motor load changes; the flux changes with load when there is a series field, & when the demagnetising effect of armature reaction is not negligible.

Note that eqn 9.5, and hence 9.8, are derived from KVL

$$E_A = V - I_A R \quad (9.9)$$

so that the straight line of fig. 9.2 is just a scaled representation of KVL !

9.5

When the motor is driving a mechanical load, the torque and speed are found from the motor mechanical characteristic and the load torque-speed characteristic, fig. 9.2; that is, the operating point (T_L, n_L) is found graphically. Fig. 9.3 shows some typical characteristics of mechanical loads.

Stability

The operating point may or may not be stable. In fig. 9.4a it is stable : if the speed suddenly increases from n to n' , the load torque T_L' will be greater than the motor torque T_M' , causing deceleration back to the operating point (n, T); the operating point will also be restored to (n, T) for a sudden decrease in speed (try it).

In fig. 9.4b, the operating point is unstable : if the speed suddenly increases from n to n' , the motor torque T_M' will be greater than the load torque T_L' , causing acceleration and further increase in speed away from the operating point (n, T); a sudden decrease in speed may result in stall (zero speed). Clearly, then, the stability of the operating point depends on the relative shapes of the motor and load torque-speed characteristics.

Speed control

Eqn 9.5 indicates that the speed may be controlled by means of the applied voltage, main flux, and the series resistance; these parameters may be adjusted manually or automatically. Although the armature current I_A appears in the equation, and hence affects speed, it is not a proper controlling parameter because it cannot be adjusted as desired, but is determined by the mechanical load, eqn 9.2.

Now a given mechanical characteristic corresponds to a particular setting of the applied voltage, field control resistor, and series resistance. If any of the settings is changed, operation shifts to another curve. Therefore the operating point may be moved from one curve to another by changing the setting of one or more of the control parameters, fig. 9.5. The speed may be kept approximately constant by automatic regulators that sense the shaft speed and adjust one of the control parameters to keep it at the set value.

Speed regulation

The speed regulation of a motor at a given load is defined by

$$SR = \frac{\text{no-load speed} - \text{speed under load}}{\text{speed under load}} \quad (9.10)$$

It is a figure of merit that indicates how constant the shaft speed is with load. For many applications, a good drive motor is one which

9.6

maintains its speed constant over a wide range of loads. The speed regulation of motors equipped with automatic speed control is almost zero. Note the analogy between speed regulation in motor operation with voltage regulation in generator operation, section 8.2.

A low value of speed regulation is not always desirable. There are applications that require the motor to change its speed with load, for example to keep the torque or output power constant. A main feature of the dc motor is that its operation can be tailored to suit any type of load requirements.

9.3 Constant-flux motors (permanent-magnet; separately-excited; shunt)

The difference between shunt and separately excited motors is that the field of a shunt motor is fed from the same source as the armature, while the field of a separately excited motor is fed from a different source, possibly at a different voltage. In both cases, constant field voltage and resistance result in constant field current (I_f does not change with load), and hence constant main field flux. Permanent magnet motors also operate with a constant main field.

If the demagnetising effect of armature reaction is neglected, the developed torque T_d will be directly proportional to the armature current I_A , eqn 9.2, so that the two variables are related by the straight line shown dotted in fig. 9.6. Armature reaction may reduce the flux Φ , and hence reduce T_d , so that the actual relationship between T_d and I_A is curved slightly below the straight line. The load torque T_L is less than the developed torque T_d due to rotational losses, eqn 9.6, so that the T_L curve is slightly below the T_d curve, fig. 9.6. The relationship between torque and current is sometimes called the torque characteristic of the motor.

For constant-flux motors, the mechanical characteristic is a straight line with a slight negative slope, eqn 9.8 and fig. 9.7. Armature reaction may reduce the useful flux and hence increase the speed, so that the mechanical characteristic curves slightly above the straight line. This upward curvature may lead to instability, section 9.2; it is avoided by designing the motor to have no demagnetising armature reaction (by the use of interpoles), and by adding a weak series field to compensate for the reduction in flux (stabilised shunt motor).

The reduction in speed with load is very small for constant-flux motors. The mechanical characteristic is said to be hard, and the motors operate in an essentially constant speed mode.

9.7

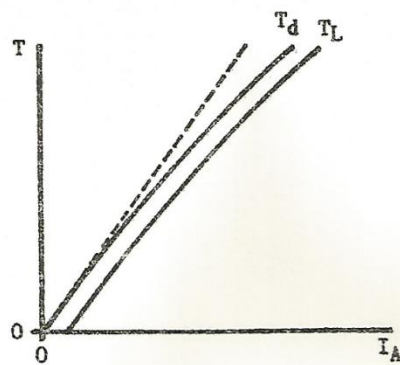


Fig. 9.6 Torque characteristic for constant-flux motors (PM, separately-excited, shunt).

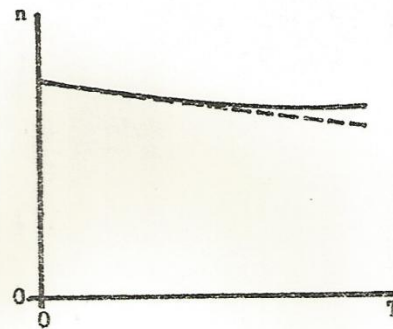


Fig. 9.7 Mechanical characteristic for constant-flux motors (PM, sep-excited, shunt).

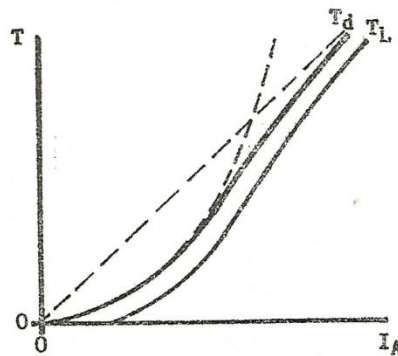


Fig. 9.8 Torque characteristic for series motor.

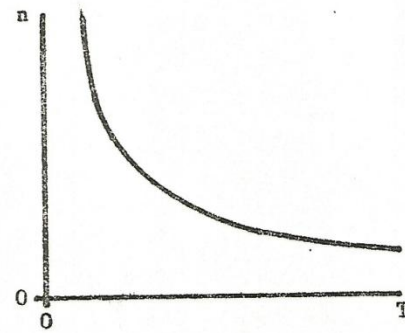


Fig. 9.9 Mechanical characteristic for series motor.

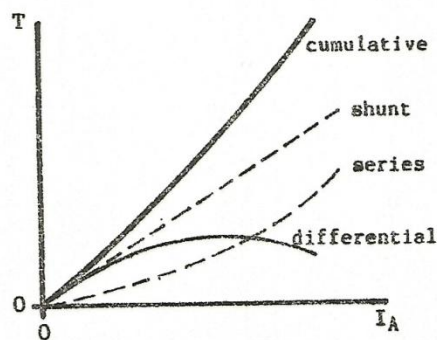


Fig. 9.10 Torque characteristics for compound motors.

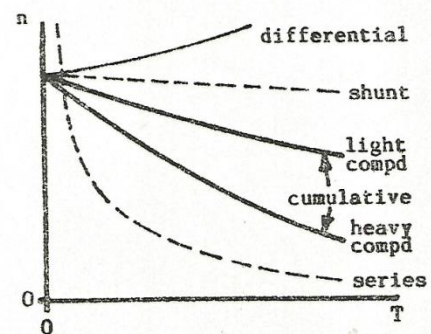


Fig. 9.11 Mechanical characteristics for compound motors.

9.8

9.4 Series motor

The main field flux of the series motor changes with load current according to the OCC; therefore the series motor is characterised by variable flux, as opposed to the constant flux motors of section 9.3.

At light loads, operation is on the linear part of the OCC, so that

$$\phi \propto I_A$$

and eqn 9.2 yields

$$T_d \propto I_A^2$$

Thus the torque characteristic follows a parabola at light loads, fig. 9.8. At heavy loads, the machine will be saturated so that the flux is almost constant, and operation approaches that of constant-flux motors

$$\phi \approx \text{constant} \quad \Rightarrow \quad T_d \propto I_A$$

The torque characteristic approaches a straight line at heavy loads, fig. 9.8.

Applying the same reasoning to the mechanical characteristic, we see that

$$\text{at light loads : } n \approx \frac{K_1}{T_d} - K_2$$

and

$$\text{at heavy loads : } n \approx K_3 - K_4 T_d \quad (\text{similar to shunt})$$

The mechanical characteristic will then have the general shape shown in fig. 9.9. The change of speed with load is quite large; the mechanical characteristic is said to be soft, and the series motor operates in a variable speed mode. The motor has a high starting torque, but the torque quickly decreases as speed goes up. At no-load the speed becomes so high it can damage the motor; therefore series motors are never run unloaded, and are always rigidly coupled to their loads (i.e. belts are never used).

9.5 Compound motors

A compound motor has both shunt and series fields. For cumulative compounding, the motor characteristics will move from shunt characteristics in the direction of series characteristics as load increases (i.e. as the series field becomes stronger); see figures 9.10 and 9.11. The actual shape of the mechanical characteristic is determined by the degree of compounding, i.e. by the ratio N_s/N_f , fig. 9.11. Differential compound motors have rising mechanical characteristics because of the

reduction in main field flux with load, fig. 9.11; therefore they are unstable (section 9.2), and are not used in practice.

9.6 Speed control

According to eqn 9.5, the parameters that can be adjusted to control speed are : the voltage applied to the armature V , the series resistance R , and the field excitation I_f (which determines main field flux).

Armature voltage control

For constant flux motors, section 9.3, the torque-speed equation 9.8 describes a straight line, fig. 9.7. The first term on the RHS gives the intercept, and the coefficient of T_a in the second term gives the slope, which is negative. In permanent-magnet and separately-excited motors, the voltage applied to the motor can be varied with the field remaining constant. Different voltages then give different intercepts, and we get a family of parallel (i.e. same slope) mechanical characteristics as in fig. 9.12. In the figure, V_r denotes rated voltage; as the applied voltage is decreased, the characteristic is shifted down. Similar downward shifts occur for the series motor, fig. 9.13; at heavy loads, the series motor approaches constant-flux operation, section 9.4, and the curves approach straight lines that are parallel as in fig. 9.12.

The simplest method of obtaining variable dc voltage is to use a voltage divider, but this method is impractical and uneconomical; it is used only for testing.

In modern applications, variable dc voltage for the armature is often obtained from a solid-state controlled rectifier, with the field fed from an uncontrolled rectifier, fig. 9.14. The firing angle of the controlled rectifier may be changed manually, but in practice it is adjusted automatically using a speed signal or armature current signal (i.e. load), or both for optimum control.

In road vehicles, the supply is itself dc, and hence needs no rectification. Voltage control is often obtained by an electronic chopper circuit, fig. 9.15. Choppers may use pulse-width modulation PWM at constant frequency, or pulse-frequency modulation PFM with constant pulse width.

Another effective method for obtaining smooth voltage control is the Ward-Leonard system, fig. 9.16. The dc motor is fed from a dc generator driven by some prime-mover (eg ac motor or Diesel engine). By varying the field excitation of the generator, the armature voltage of the motor is varied (and can be even reversed). The motor field is fed from an

exciter (small dc generator) or rectifier at constant voltage. The Ward-Leonard system is generally more expensive than a solid-state drive, but has compensating advantages for certain applications.

9.10

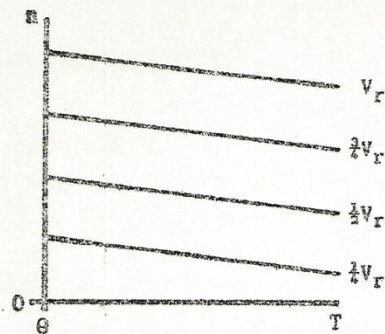


Fig. 9.12 Armature voltage control of constant-flux motors.

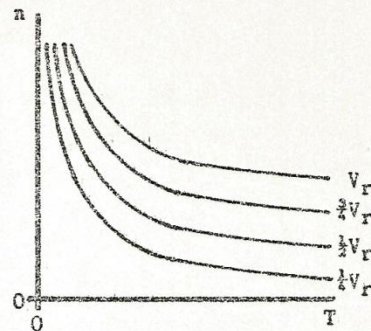


Fig. 9.13 Armature voltage control of series motor.

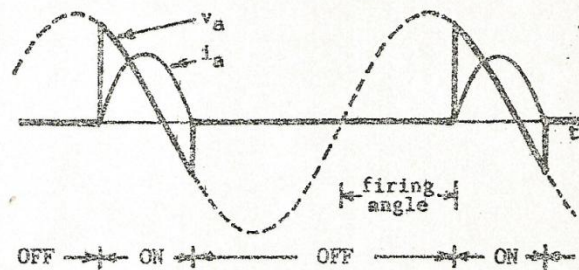
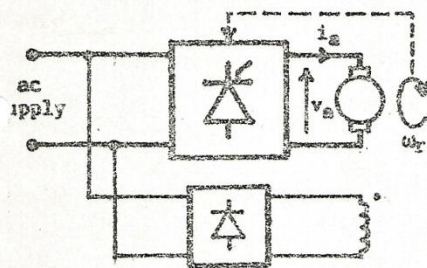


Fig. 9.14 Armature voltage control using solid-state controlled rectifier (half-wave). Field supplied from uncontrolled rectifier for constant excitation.



Fig. 9.15 Voltage control of series motor using chopped dc supply.

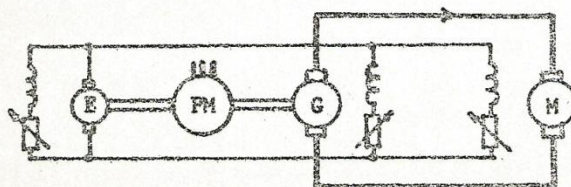
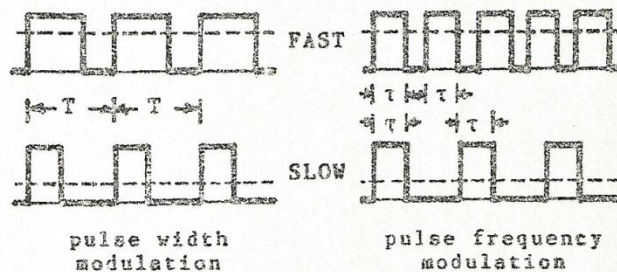


Fig. 9.16 Ward-Leonard system for armature voltage control.

9.11

Armature resistance control

For a given load torque, and hence given current, placing an external resistance in series with the armature, fig. 9.17, reduces the emf and hence speed. The increasing value of resistance increases the slope of the mechanical characteristic, eqn 9.8. Thus the hard characteristic of constant-flux motors is seen to become softer with increasing resistance in fig. 9.17a, but the intercept remains unchanged. Armature resistance control may also be used with series motors giving the family of curves shown in fig. 9.17b; at heavy loads the machine is saturated (why ?) and operation approaches that of constant-flux motors with slope increasing as resistance is increased.

Armature resistance control is inexpensive and simple to use with small motors, but it is impractical and wastes energy with large motors.

Field control

This method of speed control may be used with shunt and separately excited motors. With no external resistance in the field circuit; and with rated voltage applied to the armature, the motor will operate at constant flux and follow a certain mechanical characteristic; this is called the base case, fig. 9.18. If now the field circuit resistance is increased, the field current, and hence the main field, will be reduced, and the speed will increase according to eqn 9.5 or 9.8. We thus obtain a family of curves above the base case, fig. 9.18. The higher the field resistance, the higher the intercept and the greater the slope (i.e. the characteristic becomes softer).

The flux cannot be reduced indefinitely because the speed becomes too high and may damage the motor. Moreover, if the main field becomes too weak, the demagnetising effect of armature reaction becomes prominent (relatively large) which may lead to instability, section 9.2.

Comparison

Armature voltage control provides the best method of speed control of dc motors; indeed, it is the main reason for the continuing existence of large dc machines. The speed may be controlled from zero to maximum safe speed in either forward or reverse direction. The

control can be manual, or automatic with speed or current sensors. The constant-speed feature of constant-flux motors is retained, giving adjustable speed drives.

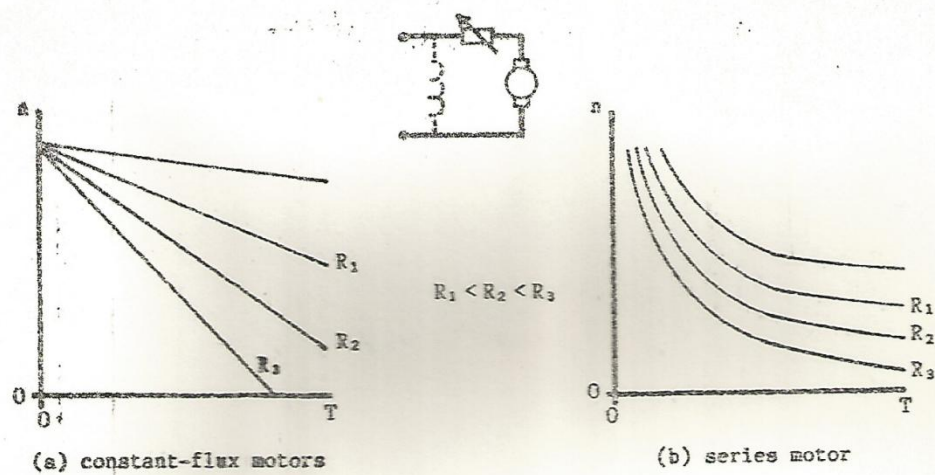


Fig. 9.17 Armature resistance control.

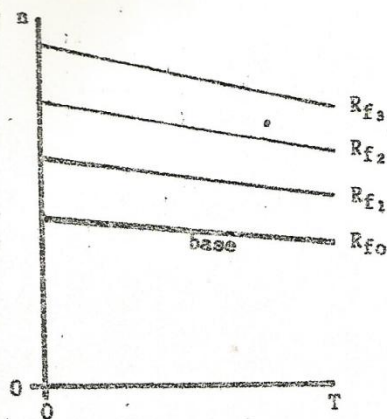


Fig. 9.18

Field control. R_{f0} is the resistance of the field winding.

$$R_{f1} < R_{f2} < R_{f3}$$

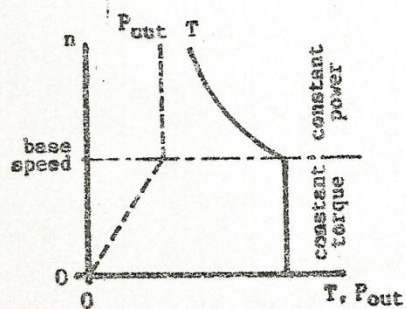


Fig. 9.19 Armature voltage control up to base speed, with field weakening to extend speed range.

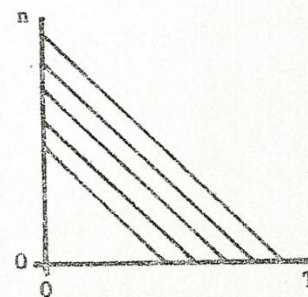


Fig. 9.20 Control motor characteristics.

9.13

Armature resistance control is cheaper than armature voltage control, but it is wasteful and less versatile. As the armature resistance increases, the mechanical characteristic becomes softer, and the motor operates at variable-speed. This type of control is sometimes used with relatively small series or permanent magnet motors.

Shunt field control is also relatively cheap (and wasteful), but it does not compete with armature voltage control : it increases speed from base value, and cannot reduce speed to zero. The mechanical characteristic becomes softer as the field resistance is increased, and there is an upper limit on the speed that can be reached, usually around 2:1 (i.e. twice base speed).

In some applications, particularly traction, both armature voltage and field control are used, fig. 9.19 : armature voltage control is used up to base speed to maintain the torque constant; above base speed, field control is used to maintain output power constant ($2\pi nT$).

Small dc motors with fixed excitation are often used in automatic control systems. They are designed to have linear mechanical characteristics with accurate voltage control down to stall (standstill) as shown in fig. 9.20.

9.7 Starting

At the moment the motor is switched on, it is at standstill, so that there is no induced emf. The entire line voltage is applied across the armature resistance since eqn 9.4 reduces to Ohm's law :

$$I_{\text{start}} = \frac{V}{R_A}$$

The starting current is therefore very high, especially for large motors which have very small armature circuit resistance. The starting current may be more than 20 times rated value, and would damage the motor unless some means is found to limit it.

Note that the problem exists only at starting because as soon as the motor begins to rotate, the emf begins to build up and thus reduce the current in accordance with eqn 9.4. Note also that the rate at which the emf builds up depends on the rate at which the motor accelerates from standstill which, in turn, depends on the starting torque; that is, a high starting torque is desirable for rapid initial acceleration (and hence rapid build-up of emf, and hence rapid reduction of the high starting current).

Direct on-line starting (DOL)

DOL starting means simply connecting the motor to the supply through a switch. This method can be used only with small motors where (a) the armature resistance is high enough to limit the starting current, and (b) the rotor inertia is small enough to allow rapid acceleration (and hence rapid build-up of emf leading to rapid reduction of current).

Variable voltage starting

Motors supplied from Ward-Leonard sets or controlled rectifiers can be started by raising the supply gradually from zero. The low initial voltage results in a reduced starting current.

Resistance starting

This is the most common method of starting dc motors. A specially designed variable resistor is connected in series with the armature, fig. 9.21. When the moving contact is moved from the OFF position to the START position, all sections of the starting resistor are in the circuit so that the starting current is limited to

$$I_{\text{start}} = \frac{V}{R_A + R_{\text{start}}}$$

The value of R_{start} is chosen to limit the starting current to a safe value, usually 1.5-2.5 times rated current. Although the starting current is still greater than the rated current, it is considered safe because it flows only for a short time. Moreover, a relatively high current is needed to obtain a high torque for rapid acceleration.

As the motor builds up speed (and hence emf), the starting resistance is cut out section by section until it is totally out of the circuit. During this process, the starting current i and the induced emf e_A follow stepped curves of the forms shown in fig. 9.22. In principle, a given section is cut out when the current has fallen to some minimum value, say rated current; upon cutting out the section, the current will jump up again to a value limited by the sections remaining in the circuit (maximum safe value).

During starting, full voltage must be applied to the shunt field winding to make the flux maximum; this maximizes starting torque, eqn 9.2, maximizes emf build-up, eqn 9.1, and prevents overspeed (the high starting current may cause severe armature reaction, i.e. reduce the flux). For this reason, the starting resistor is connected in the armature circuit and not in the line, and the field control resistor is shorted out during starting.

9.15

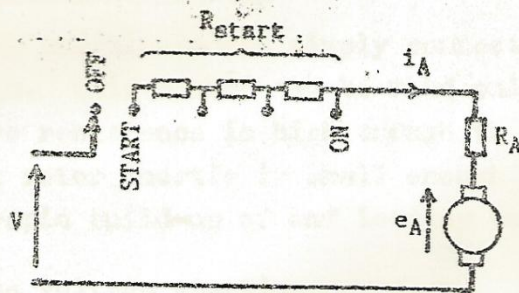


Fig. 9.21
Resistance starting.

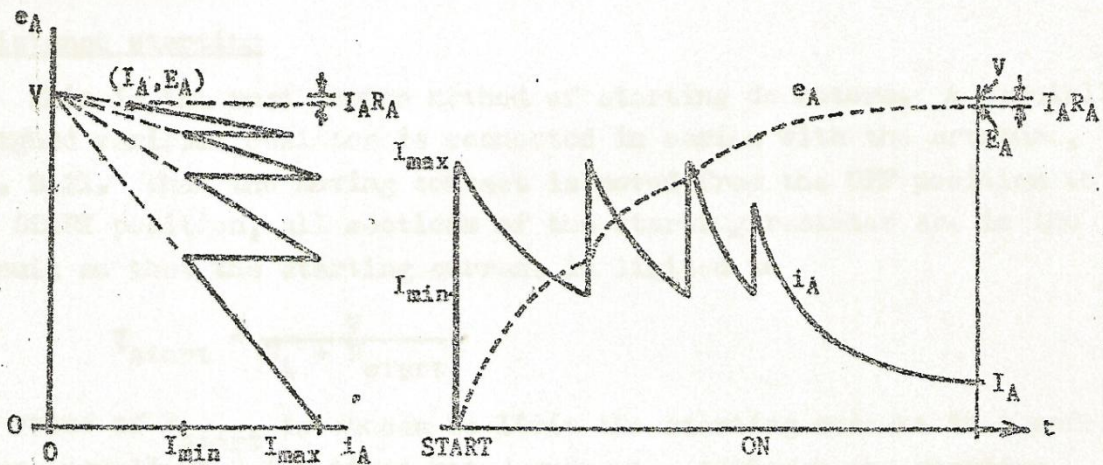
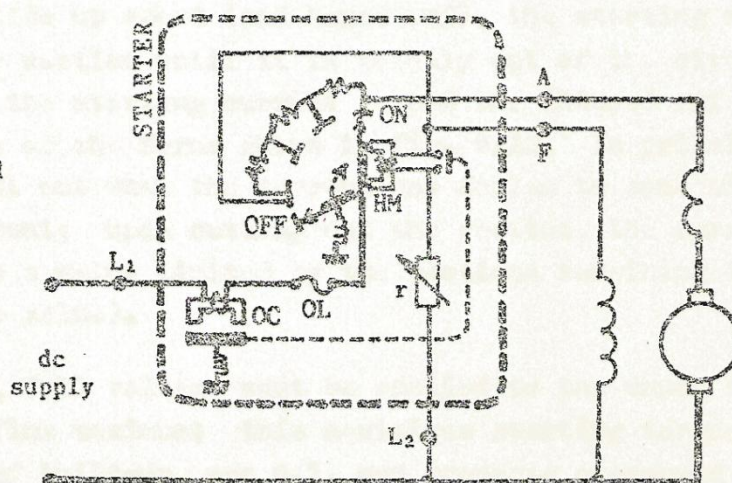


Fig. 9.22 Variation of armature current and induced emf during starting. Diagrams correspond to a starting resistor of three sections switched by means of a current-sensitive relay.

Fig. 9.23

Typical 4-point manual starter.

- OL: thermal overload protection;
- OC: electromagnetic overcurrent protection;
- HM: holding magnet (undervoltage protection);
- r: undervoltage adjustment.



9.19

hence regeneration slows the motor down. Regenerative braking uses this principle to aid in stopping the motor or in slowing it down; regeneration is achieved by strengthening the field or by reducing the applied voltage. The main advantage of regenerative braking is the saving of energy, which is returned to the supply and not dumped as heat as in the other methods of braking. It is often used in electric trains to exploit downhill runs, and in cranes to exploit the descending part of the duty cycle. Regenerative braking can be used only if the electric supply is capable of accepting electrical energy from the motor (eg chargeable batteries or dc mains); standard controlled rectifiers cannot accept electrical power from the motor unless they are modified for the purpose (eg by the inclusion of inverters). In regenerative braking, the braking action stops when the speed becomes low enough to reduce the emf below the terminal voltage.

A strong braking effect down to zero speed is obtained by plugging (or counter-current braking). The supply connections to the armature are reversed, fig. 9.25, so that the supply and armature emf act as series sources aiding each other to circulate a heavy counter-current

$$I_A = \frac{E_A + V}{R}$$

The machine operates in the generating mode with a heavy current, and hence with a strong braking torque. A series limiting resistor, R_p , is inserted in the circuit to avoid damaging currents; if the starting resistor is used as R_p , the plugging current will be twice starting current (i.e. up to five times rated current). During plugging, the kinetic energy of the rotating parts plus heavy power from the supply (VI_A) are dissipated in the armature winding and the limiting resistor R_p . The supply must be disconnected from the motor at the instant the speed reaches zero, otherwise the motor will run in the reverse direction. Plugging involves such heavy currents and high mechanical stresses that it is used only with small motors.

9.20

9.9 Modes of operation

The four-quadrant diagram of fig. 9.26 helps clarify the various modes of operation of a dc motor. The first quadrant corresponds to standard motor operation in one direction, while the third quadrant corresponds to motor operation in the reverse direction. The second and fourth quadrants correspond to generator operation.

Taking the first quadrant as reference, it is seen that motor operation in the reverse direction, third quadrant, requires reversal of either the applied voltage or the field current. If both are reversed at the same time, motor operation will continue in the same direction, first quadrant.

If initial operation is in the first quadrant, then the second quadrant corresponds to dynamic or regenerative braking. Plugging also shifts operation to the second quadrant, but attempts to continue to the third; the supply is disconnected when the operating point passes through zero speed. If initial operation is in the third quadrant, i.e. in the reverse direction, then dynamic braking, regenerative braking, and plugging occur in the fourth quadrant.

For a lift or crane, we have :-

- quadrant I : motor raises load;
- quadrant III : motor lowers load;
- quadrant II : motor brakes upward (inertia) motion of load;
- quadrant IV : load moves down by its own weight while motor applies a braking torque to keep speed constant.

9.10 Applications

DC motors are less common than ac motors because ac motors are cheaper, more robust, and require less maintenance, and because standard mains are ac. However, there are two main types of application for which dc motors are more suitable than ac motors : battery-operated equipment, and applications requiring accurate or flexible control of speed or torque.

Battery-operated equipment includes small portable apparatus (such as cassette recorders, etc.), cordless tools, and toys, as well as electric drives in road vehicles. These are usually permanent-magnet or shunt (fixed-excitation) motors, but occasionally series motors. The high starting torque of the series motor makes it suitable

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for self-starter duty in cars. Electric vehicles employ permanent-magnet or series motors, with speed control by means of choppers (armature voltage control) or armature series resistance.

The accurate control of dc motors makes them suitable for servomotor duty in automatic control systems. The motors in such applications generally have small power rating (less than 1 KW), and are required to drive a load in accordance with a control signal applied to the armature (armature voltage control). They are usually constant field motors (PM or separately-excited) designed to have a low moment of inertia for quick response, and linear mechanical characteristics for accurate control, see fig. 9.20.

The flexibility of control of dc motors makes them suitable for certain heavy power applications such as lifts, cranes, and electric traction (electric trains), as well as certain drives in heavy industry. These applications can involve frequent changes in speed, stops and starts, and possibly reversals. The hard characteristics of shunt motors with armature voltage control are ideal for adjustable-speed drives, while the softer characteristics of compound and series motors are sometimes exploited in traction (locomotives) to do without different gear ratios.